Anisotropic flow measurements from ALICE

Quark Matter 2011

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Utrecht University

for the ALICE Collaboration

Outline

- What are the properties of hot and dense matter created at the LHC in Pb-Pb collisions?
- Elliptic flow
  - charged particles v_2
  - event-by-event fluctuations in v_2
  - identified particles v_2
  - v_2 at high-p_t
- directed, triangular, quadrangular and pentangular flow
- what constraints do we have on η/s and the initial conditions?

Talks:

A. Bilandzic

M. Krzewicki

A. Dobrin

I. Selyuzhenkov

A. Adare

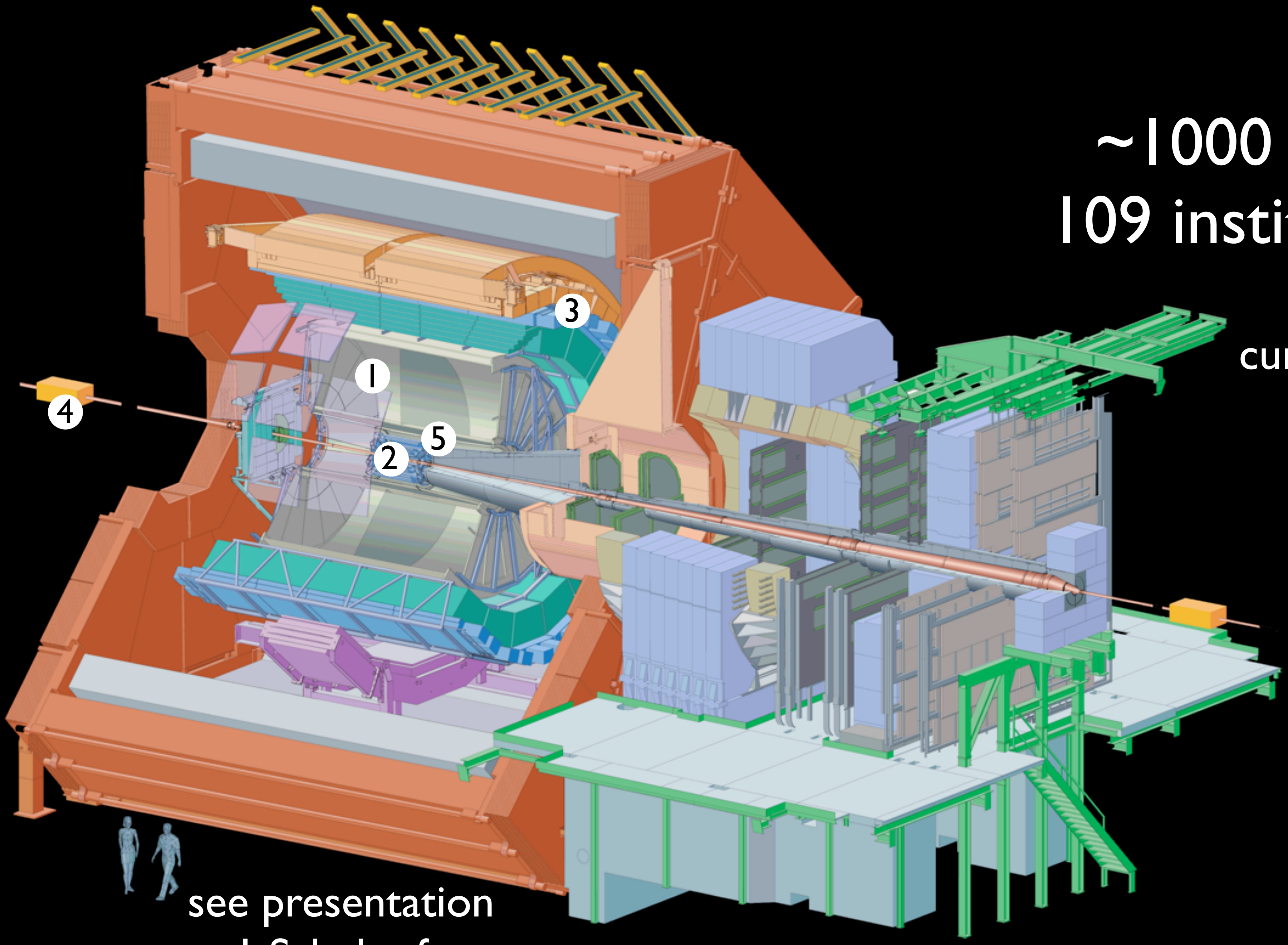
Posters:

G. Eyyubova

D. Kim

C. Ivan

B. Chang



~1000 collaborators from
109 institutes in 31 countries

currently used in flow analysis

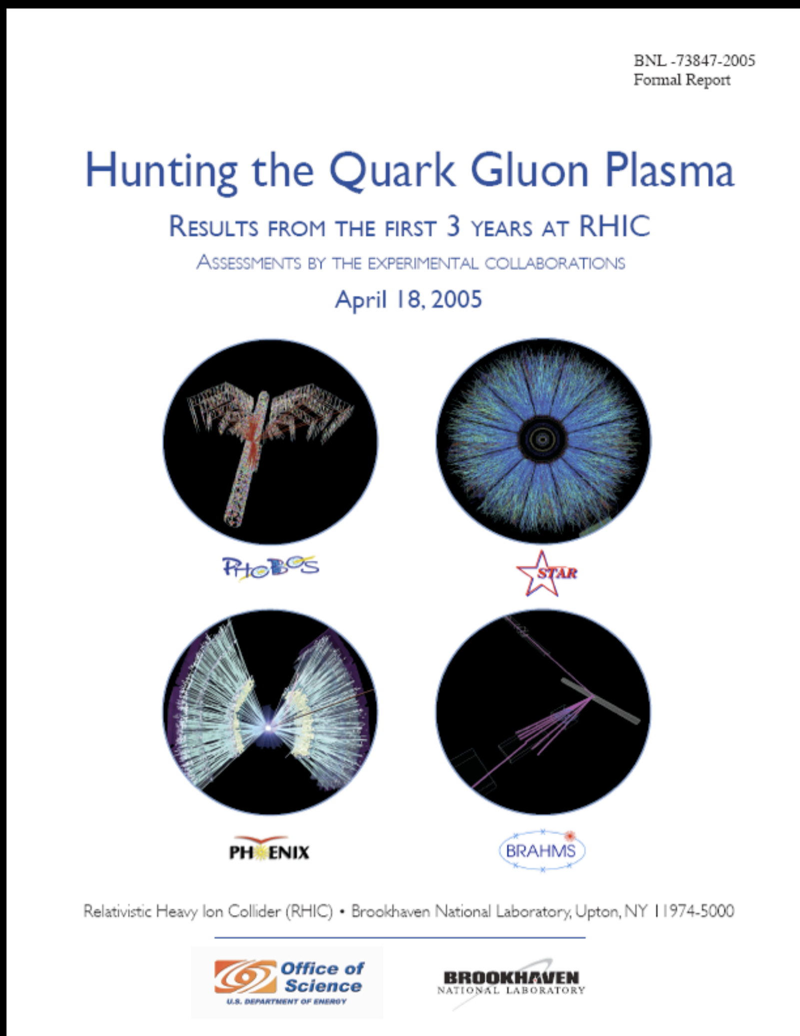
1. TPC
2. ITS
3. TOF
4. ZDC
5. VZERO

see presentation
J. Schukraft

ALICE is well suited for anisotropic flow studies

RHIC Scientists Serve Up "Perfect" Liquid

New state of matter more remarkable than predicted - raising many new questions - April 18, 2005


BNL -73847-2005
Formal Report

Hunting the Quark Gluon Plasma

RESULTS FROM THE FIRST 3 YEARS AT RHIC

ASSESSMENTS BY THE EXPERIMENTAL COLLABORATIONS

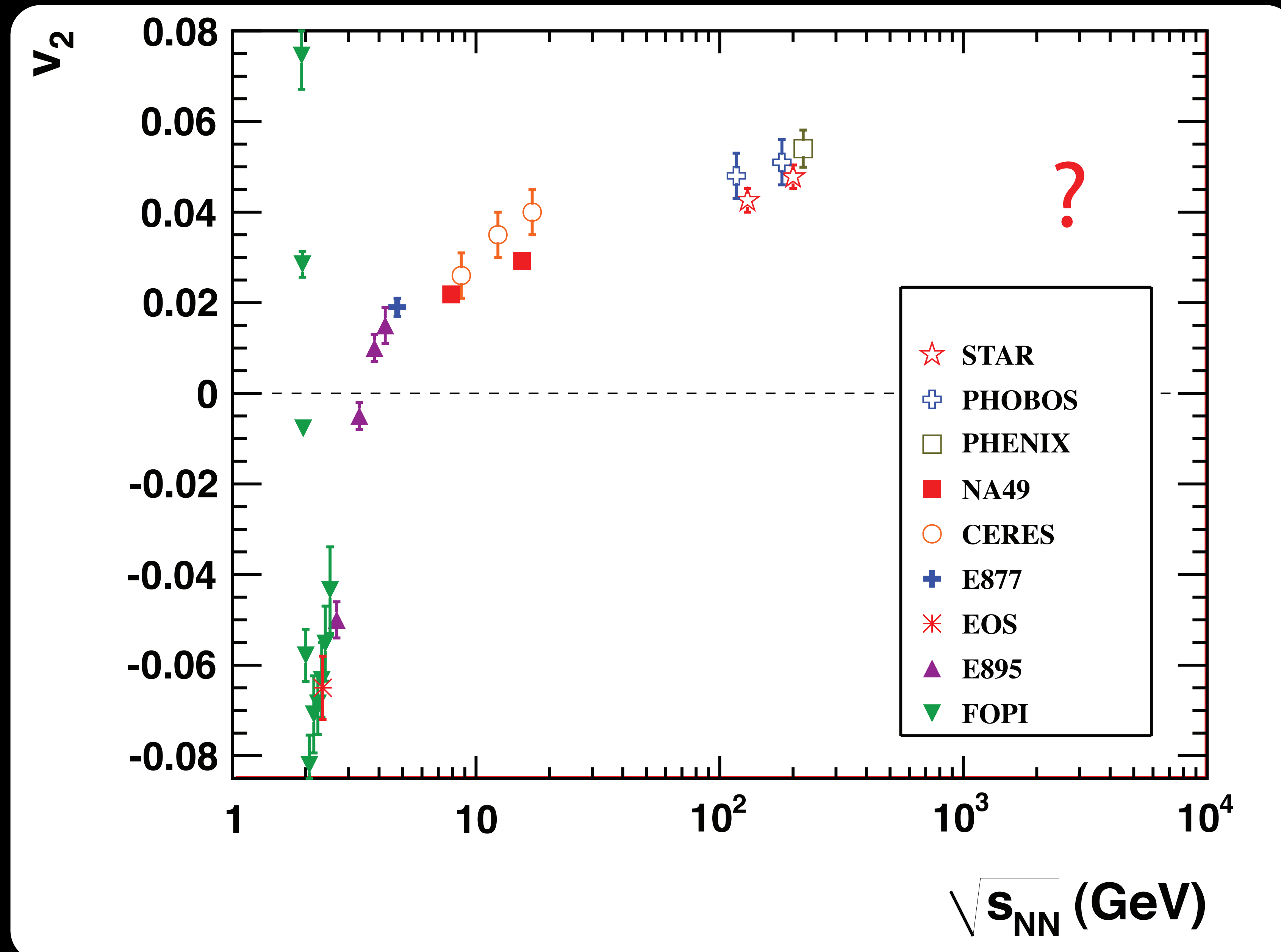
April 18, 2005

PHOBOS STAR PHENIX BRAHMS

Relativistic Heavy Ion Collider (RHIC) • Brookhaven National Laboratory, Upton, NY 11974-5000

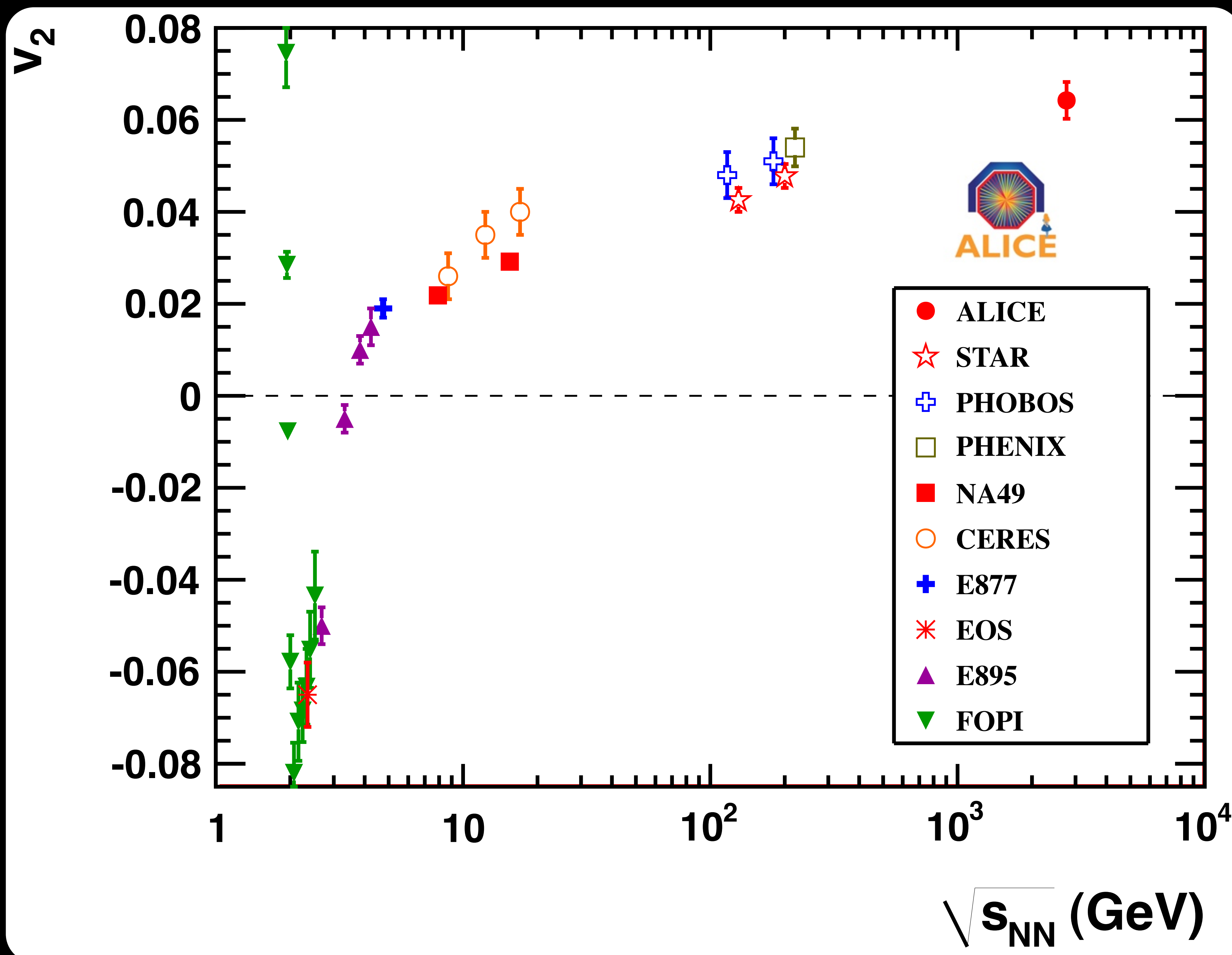
Office of Science U.S. DEPARTMENT OF ENERGY

BROOKHAVEN NATIONAL LABORATORY



What to expect at the LHC: still the perfect liquid or are we approaching the viscous ideal gas?

The Perfect Liquid

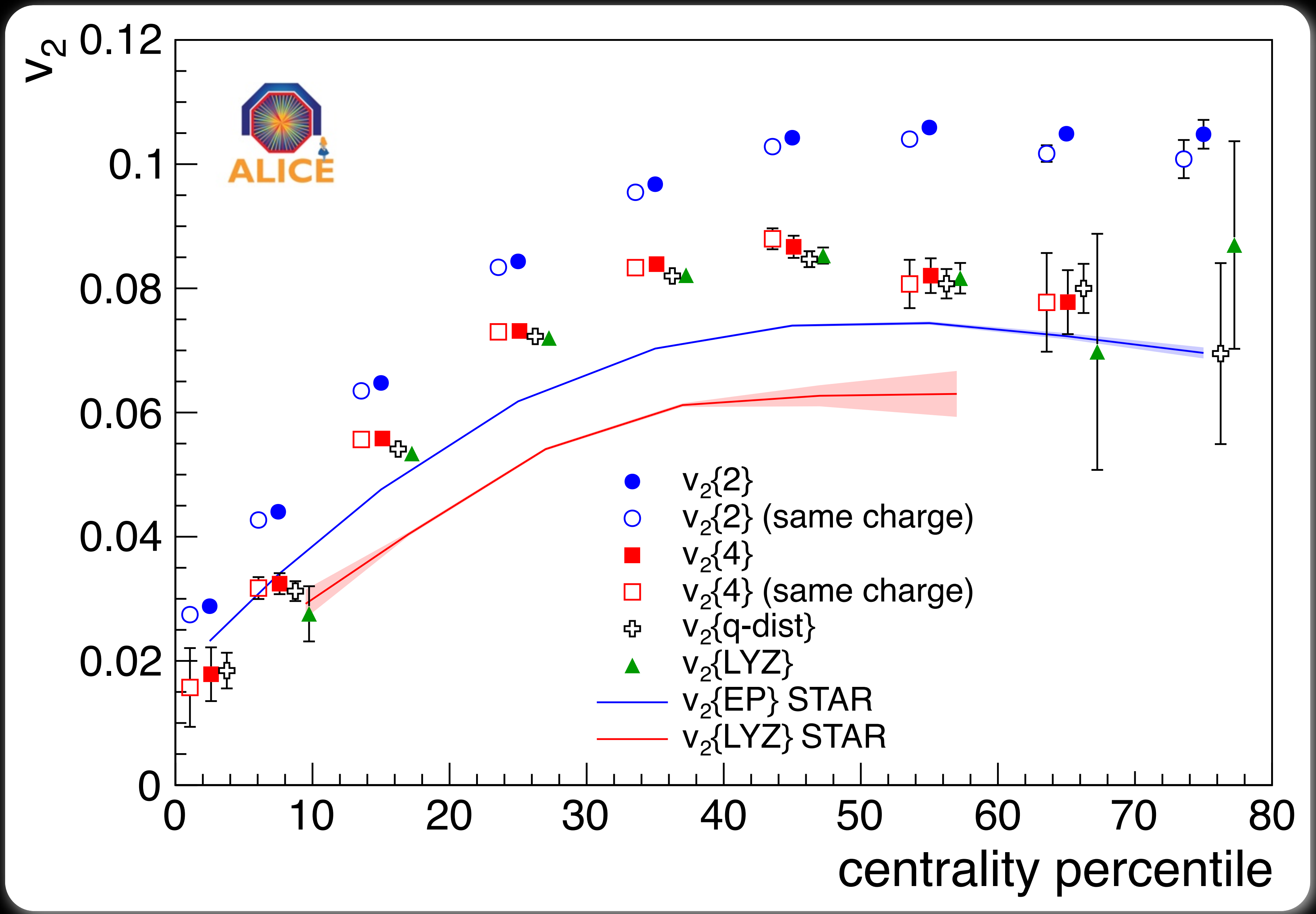


K. Aamodt et al. (ALICE Collaboration)
PRL 105, 252302 (2010)

The system produced at the LHC behaves as a very low viscosity fluid (a perfect fluid)

v_2 versus centrality in ALICE

K. Aamodt et al. (ALICE Collaboration)
PRL 105, 252302 (2010)



v_2 increases up to about 30% for more peripheral centralities

Two bands of v_2 results: two and multi-particle estimates

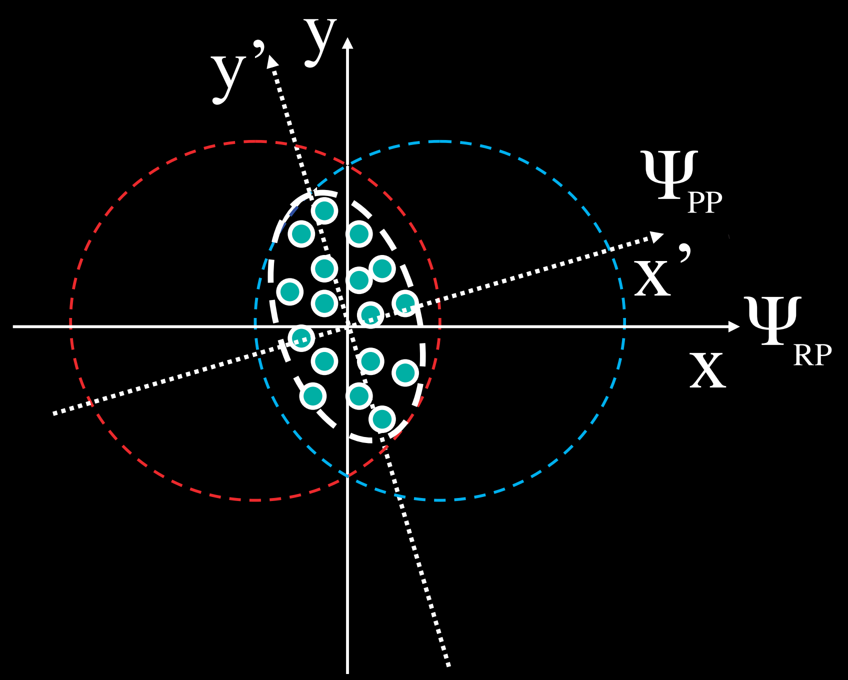
Flow Analysis Methods

flow analysis methods have different sensitivity to nonflow and fluctuations

For flow analysis in ALICE we use and compare all of them

In this talk I focus on the cumulants

Borghini, Dihn and Ollitrault, PRC 64, 054901 (2001)



$$v_n^2\{2\} = \bar{v}_n^2 + \sigma_v^2 + \delta$$

$$v_n^2\{4\} = \bar{v}_n^2 - \sigma_v^2$$

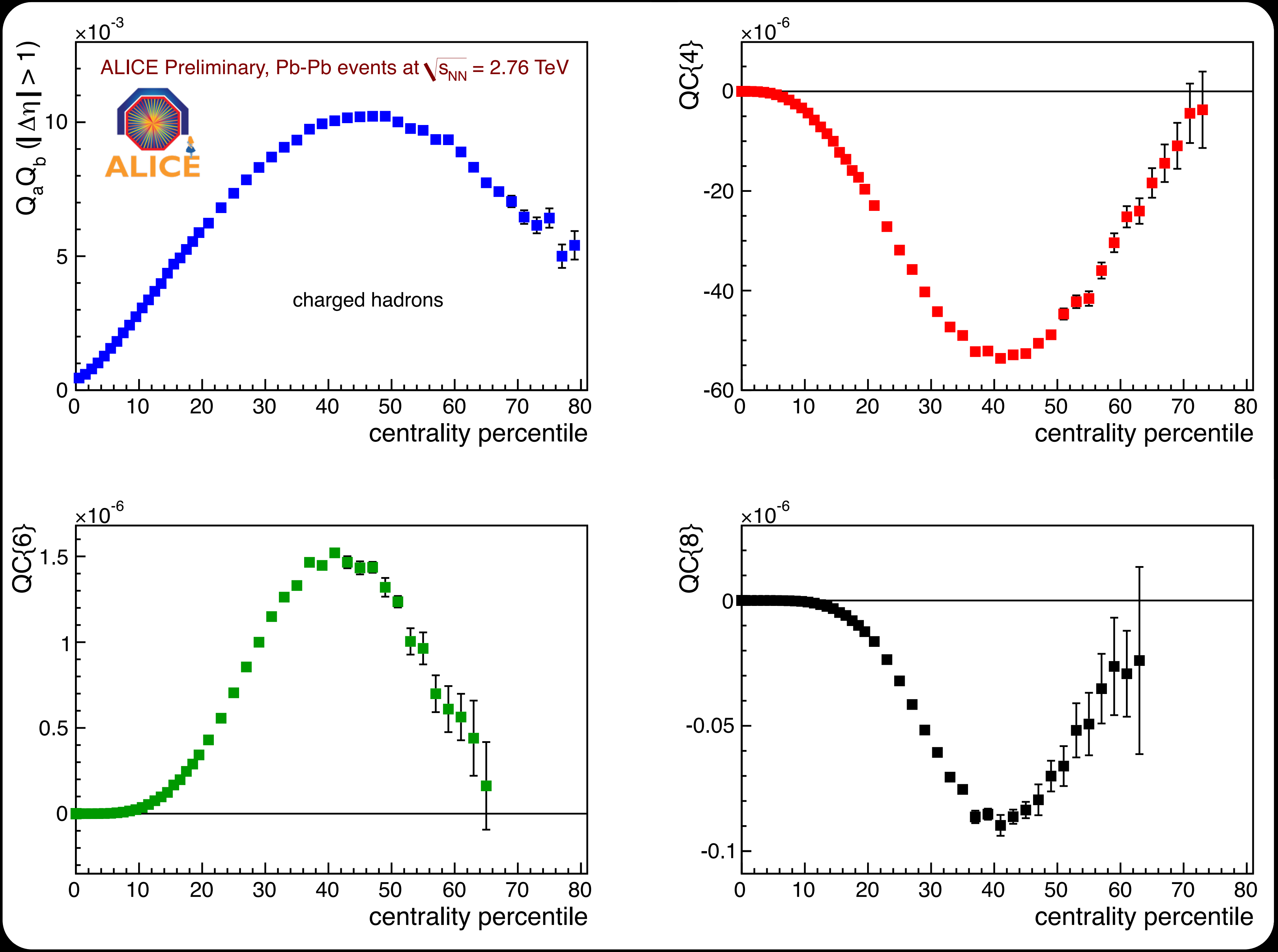
$$v_n^2\{6\} = \bar{v}_n^2 - \sigma_v^2$$

$$v_n^2\{8\} = \bar{v}_n^2 - \sigma_v^2$$

excellent opportunity to study flow fluctuations and get handle on initial conditions!

v_2 from cumulants

Method used : A.Bilandzic, R.Snellings, S. Voloshin,
Phys.Rev. C83 (2011) 044913



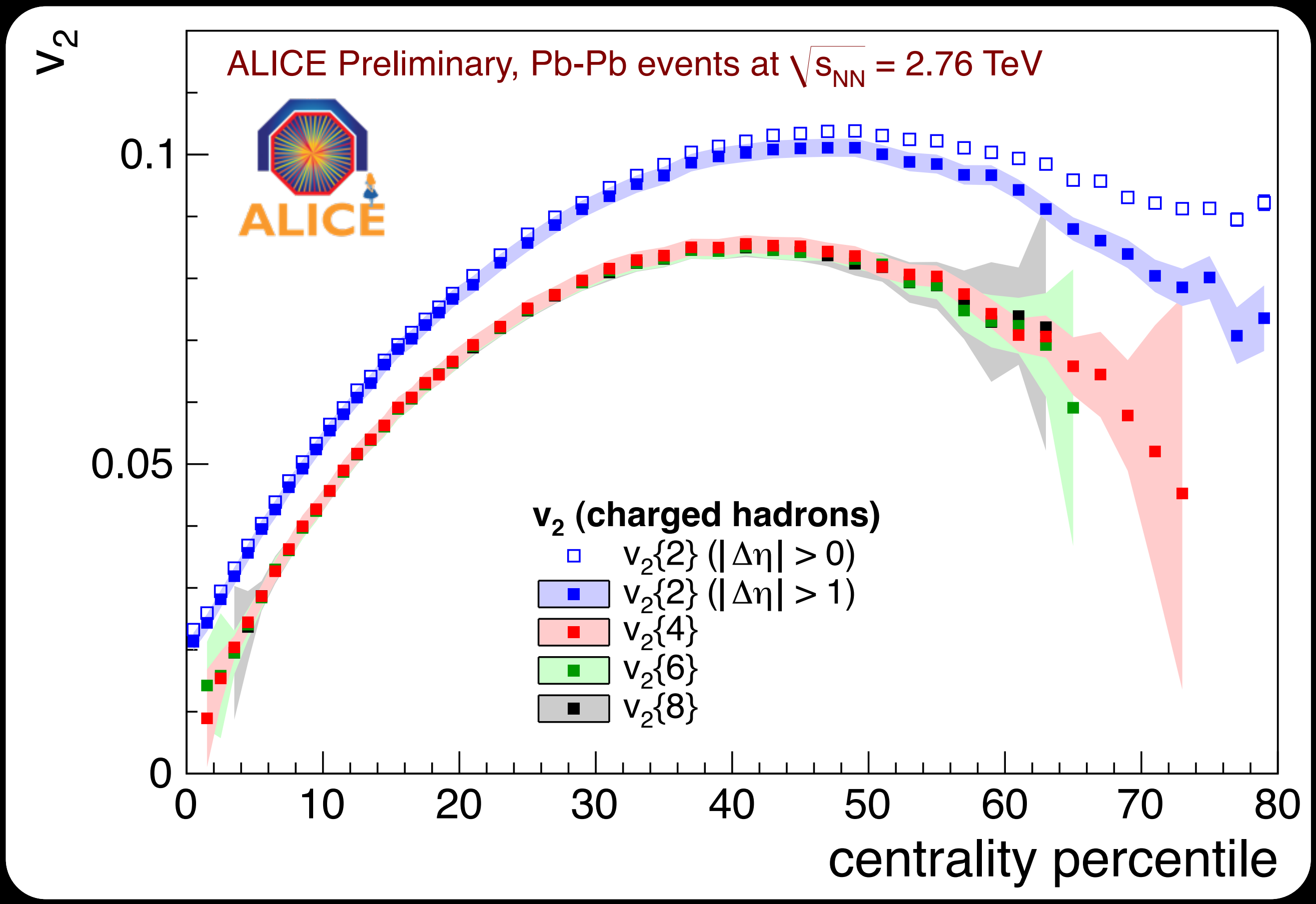
$$QC\{2\} = v^2\{2\}$$
$$QC\{4\} = -v^4\{4\}$$
$$QC\{6\} = 4v^6\{6\}$$
$$QC\{8\} = -33v^8\{8\}$$

see presentation A. Bilandzic

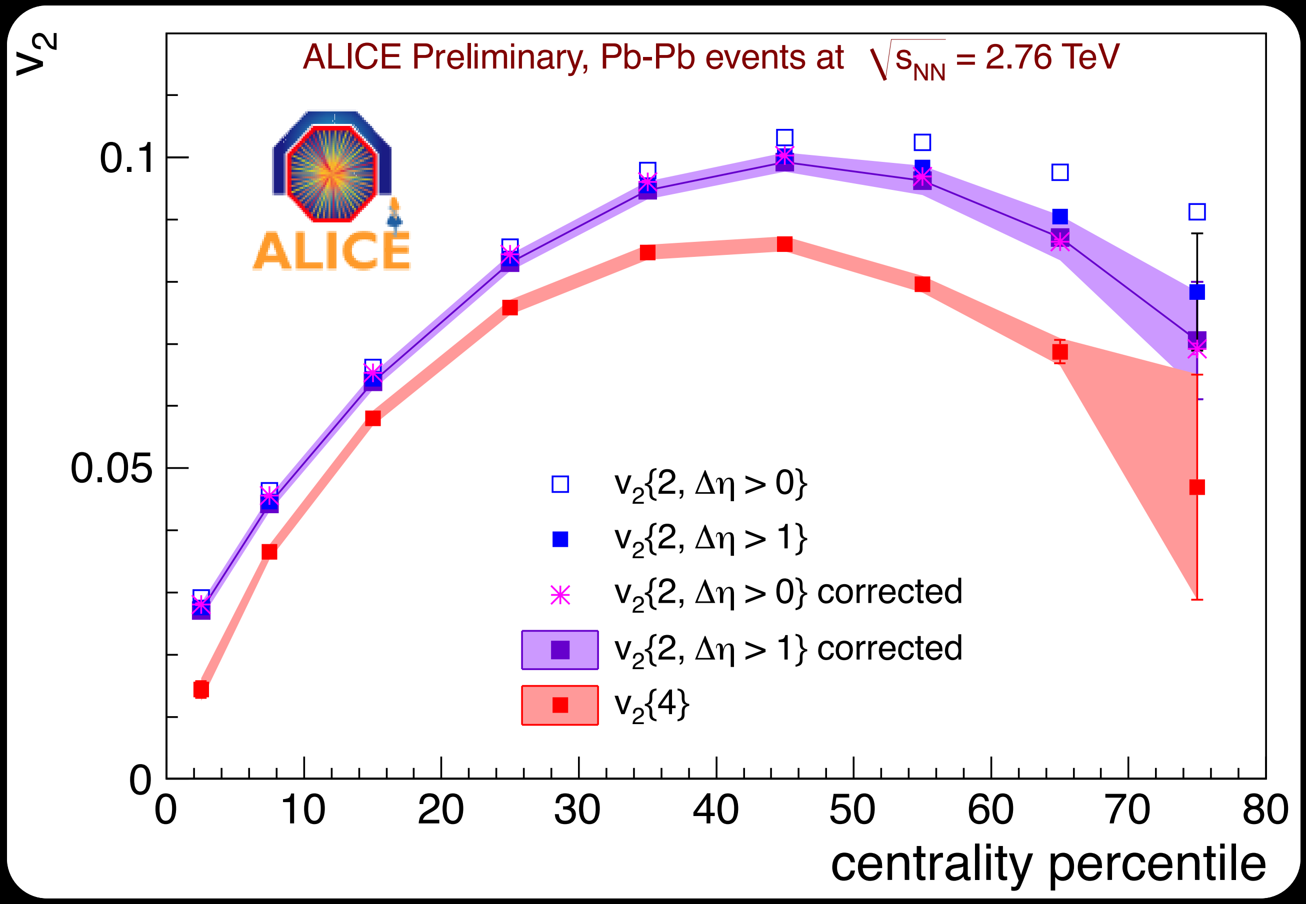
for centrality see presentation A. Toia

cumulants show behavior as expected when correlations are dominated by collective flow

v_2 versus centrality in ALICE



see presentation A. Bilandzic



Two particle v_2 estimates depend on $\Delta\eta$
Higher order cumulant v_2 estimates are consistent within uncertainties

Two particle v_2 estimates are corrected for nonflow based on HIJING
The estimated nonflow correction for $\Delta\eta > 1$ is included in the systematic uncertainty

Flow Fluctuations

when nonflow is negligible!

in limit of small (not necessarily Gaussian) fluctuations

$$v_n^2\{2\} = \bar{v}_n^2 + \sigma_v^2$$

$$v_n^2\{4\} = \bar{v}_n^2 - \sigma_v^2$$

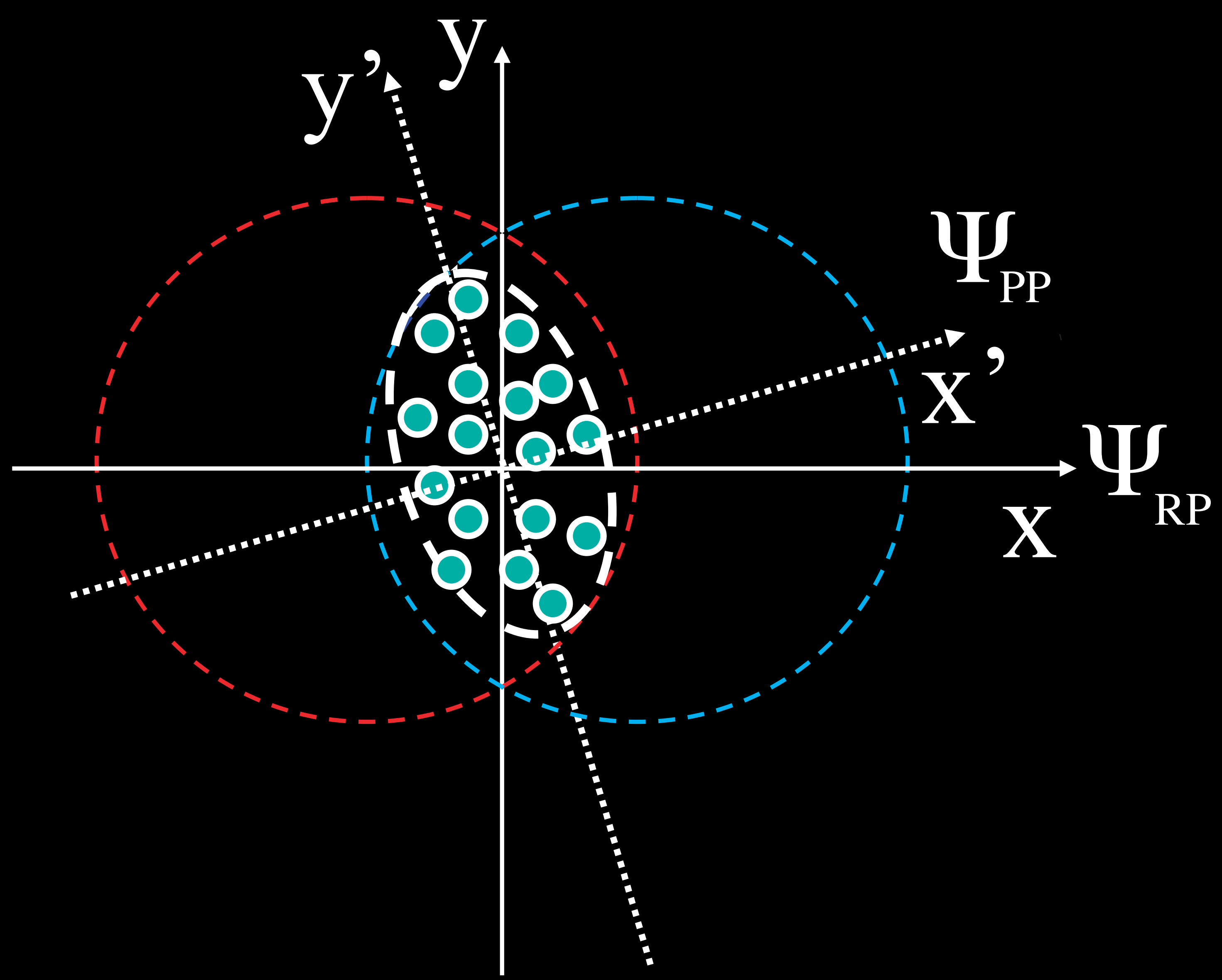
$$v_n^2\{2\} + v_n^2\{4\} = 2\bar{v}_n^2$$

$$v_n^2\{2\} - v_n^2\{4\} = 2\sigma_v^2$$

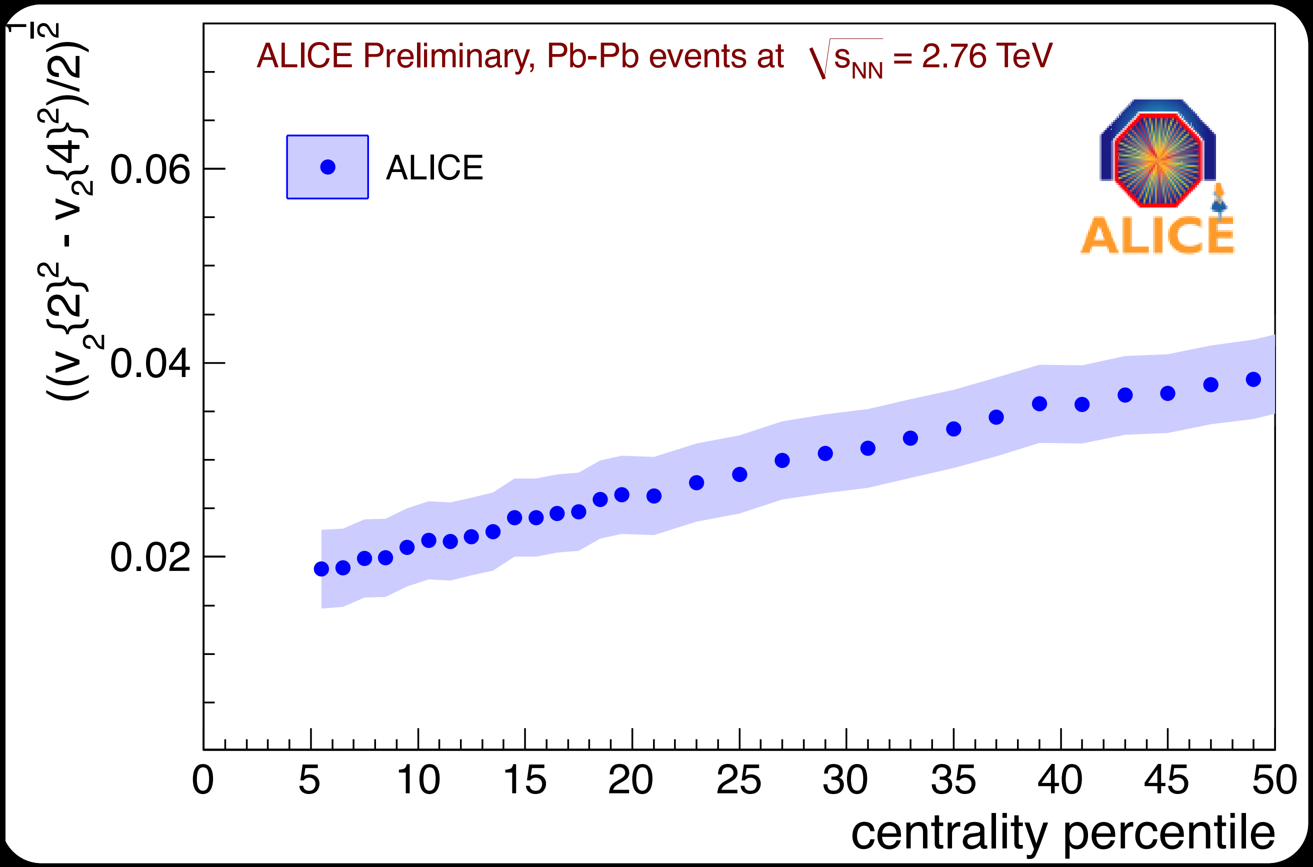
in limit of only (Gaussian) fluctuations

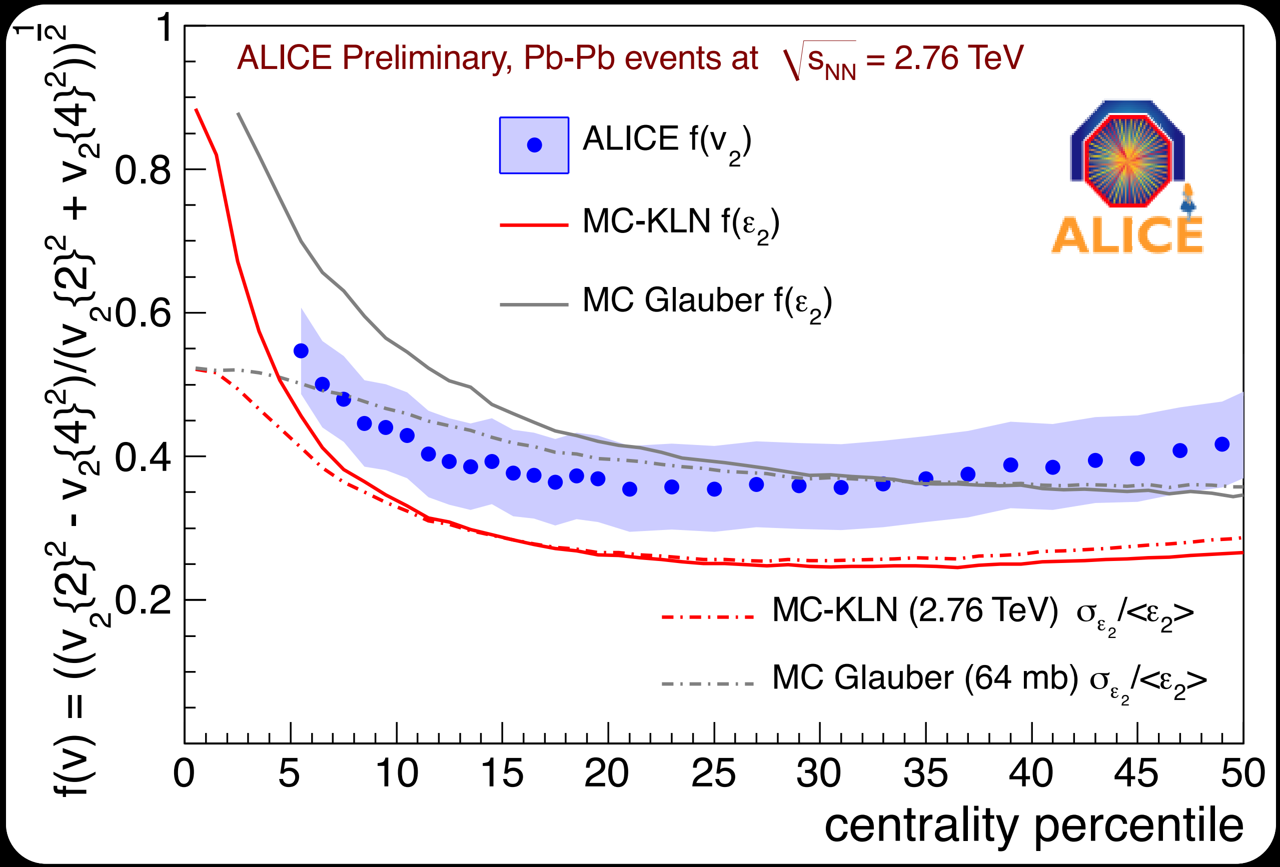
$$v_n\{4\} = 0$$

$$v_n\{2\} = \frac{2}{\sqrt{\pi}}\bar{v}_n$$



v_2 Fluctuations





$$\sigma_{v_n} \simeq [\frac{1}{2}\left(v_n^2\{2\} - v_n^2\{4\}\right)]^{\frac{1}{2}}$$

$$\frac{\sigma_{v_n}}{v_n} \simeq \left(\frac{v_n^2\{2\} - v_n^2\{4\}}{v_n^2\{2\} + v_n^2\{4\}}\right)^{\frac{1}{2}}$$

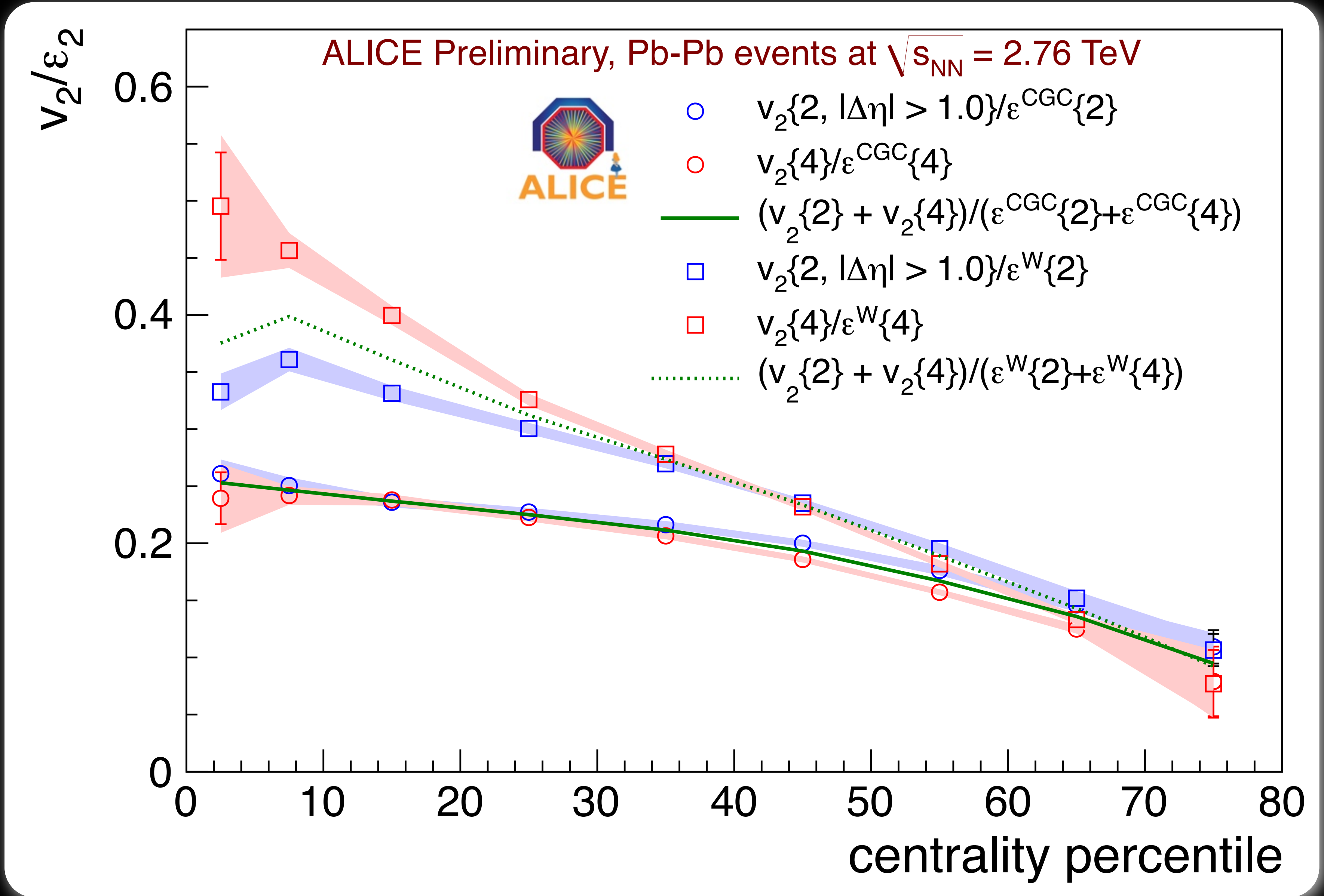
For more central collisions the data is between MC Glauber and MC-KLN CGC

v_2/ε_2

$$v_2 \propto \varepsilon_2$$
$$v_2\{n\} \propto \varepsilon_2\{n\}$$

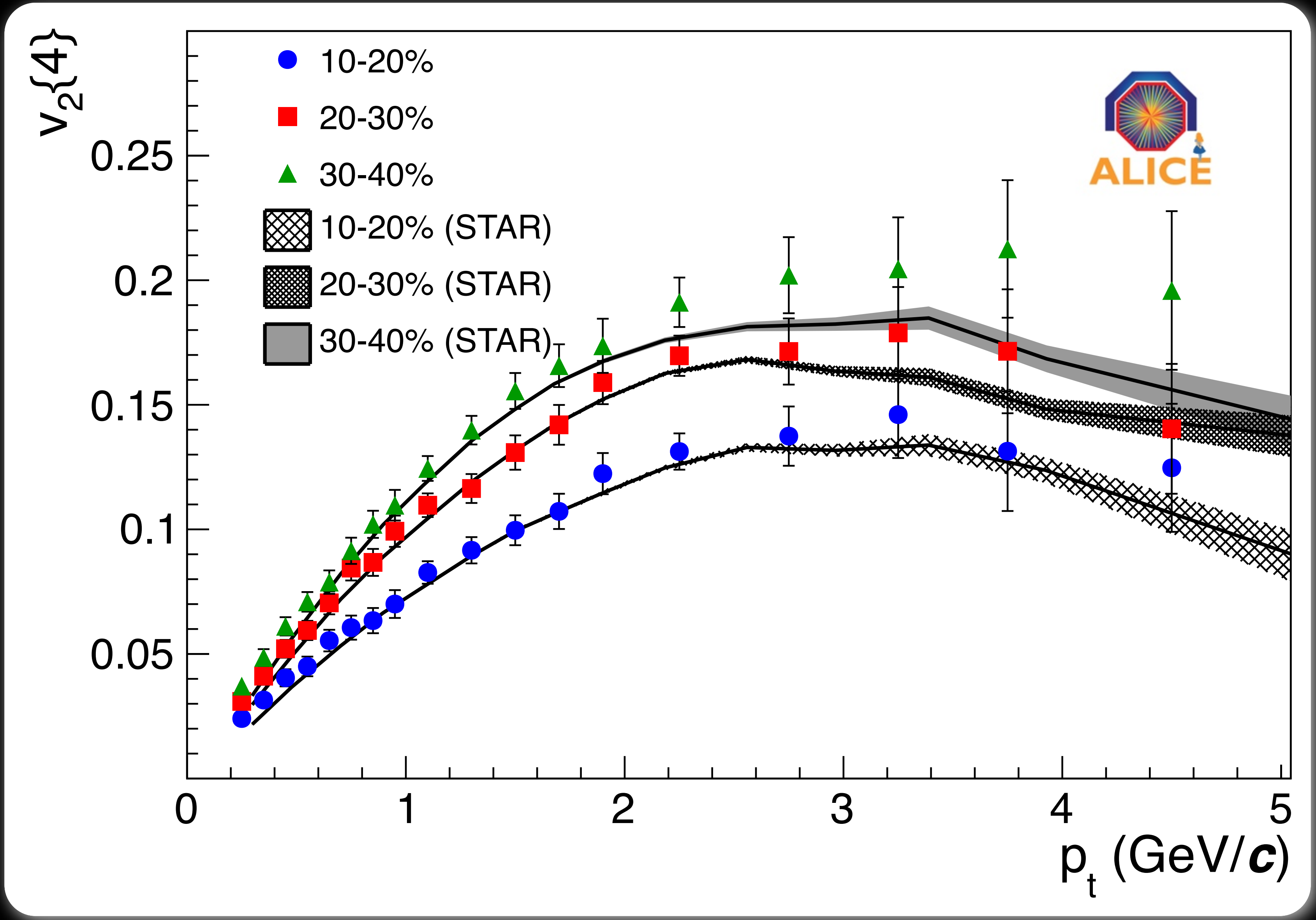
the lines show the estimate of v_2/ε from:

$$\frac{v_n\{2\} + v_n\{4\}}{\varepsilon_n\{2\} + \varepsilon_n\{4\}}$$



The ratio $v_2\{2\}/\varepsilon_2\{2\}$ is different than $v_2\{4\}/\varepsilon_2\{4\}$ for MC Glauber calculation because fluctuations are larger than in data

v_2 as function of p_t

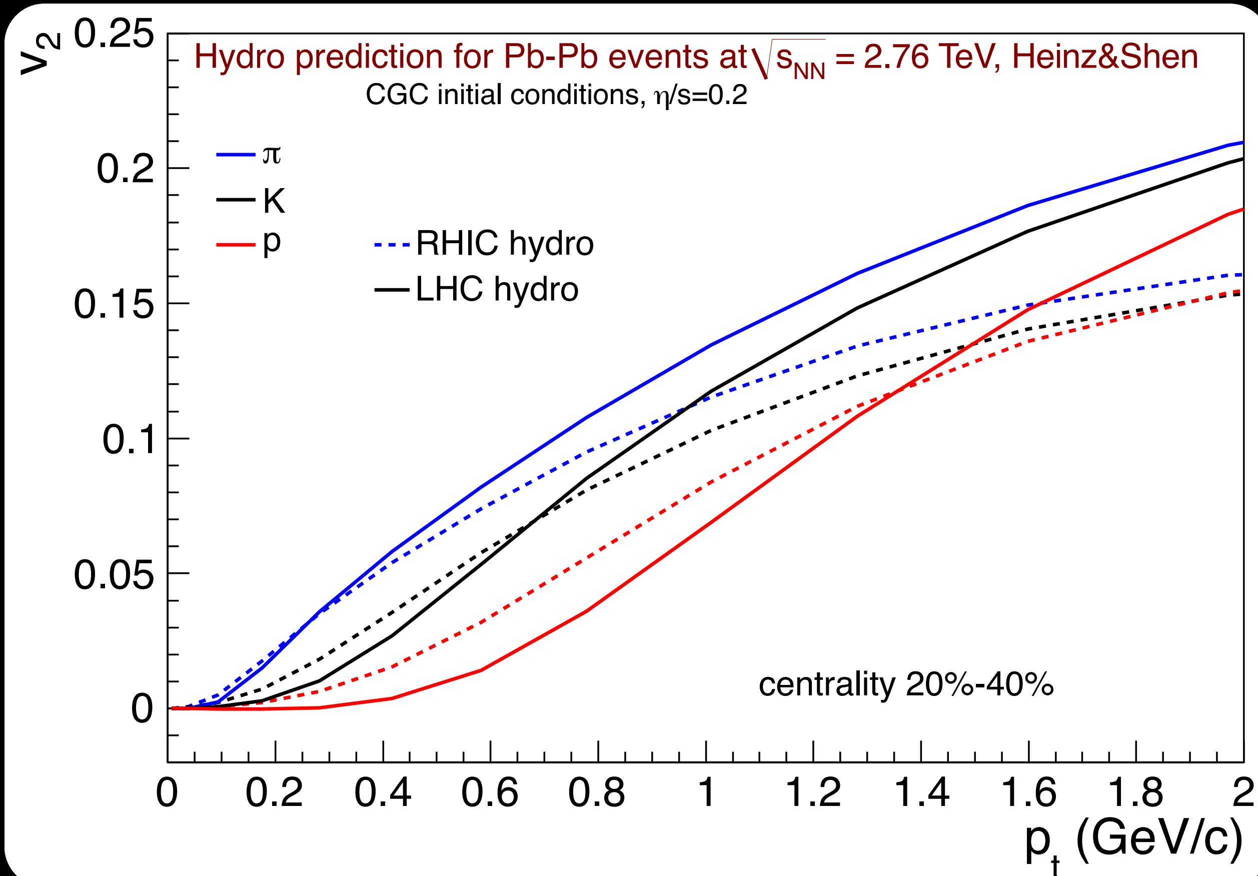


K. Aamodt et al. (ALICE Collaboration)
PRL 105, 252302 (2010)

Elliptic flow as function of transverse momentum does not change much from RHIC to LHC energies, can we understand that?

v_2 for identified particles

Hydro: Shen, Heinz, Huovinen & Song, arXiv:1105.3226

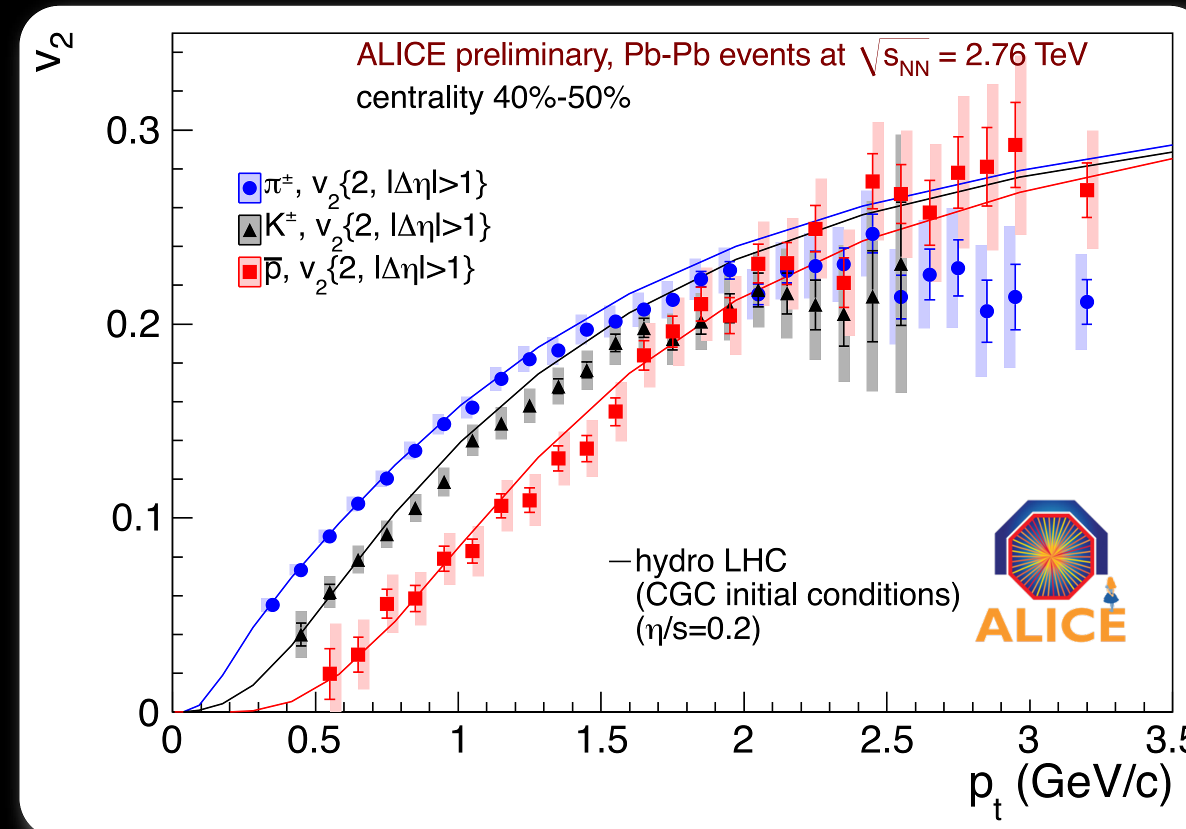


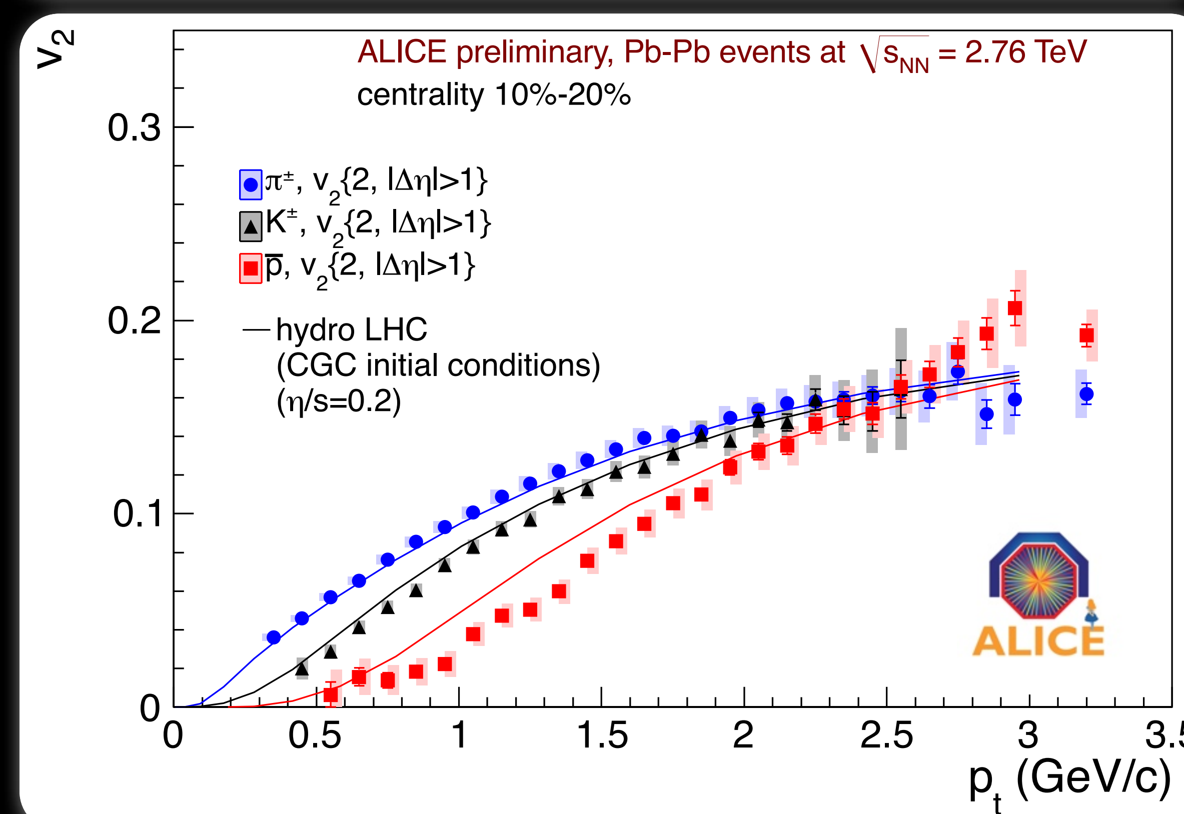
hydro models predict larger mass splitting

data shows mass splitting and agrees well with hydro predictions for mid-central collisions

for more central collisions the anti-proton flow is not described by the same calculations

Hydro: Shen, Heinz, Huovinen & Song, arXiv:1105.3226

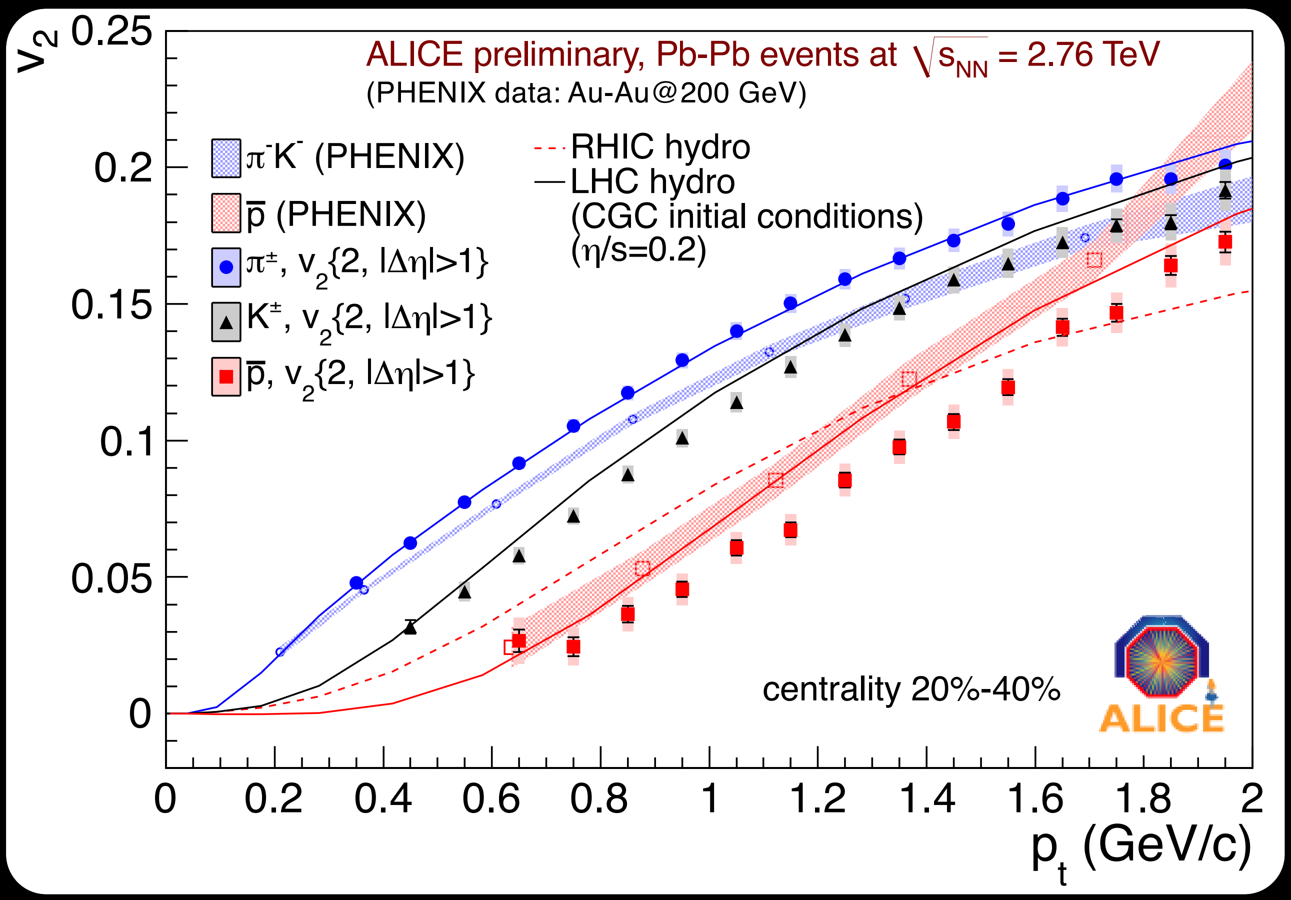


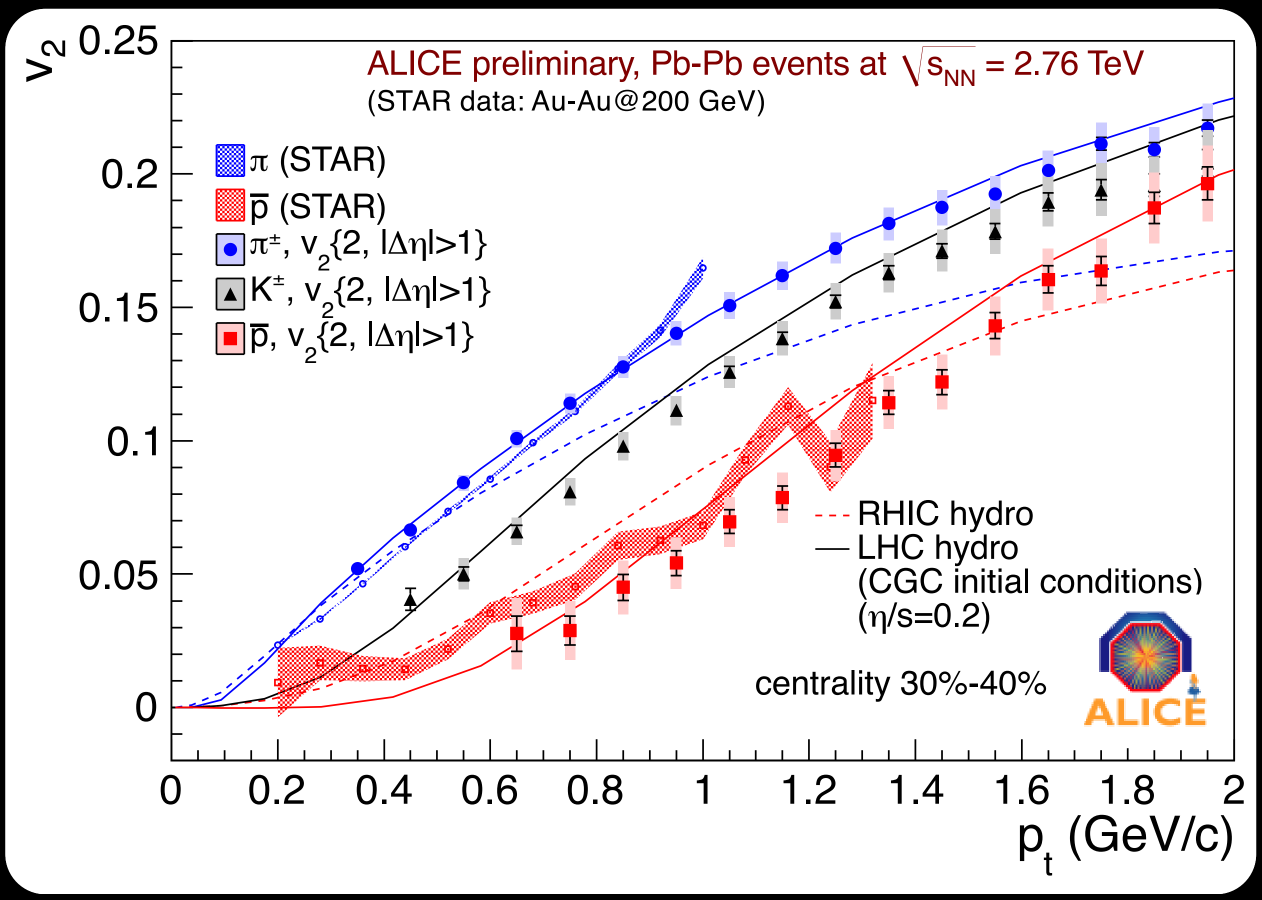


see presentation M. Krzewicki

v_2 for identified particles

Hydro: Shen, Heinz, Huovinen & Song, arXiv:1105.3226





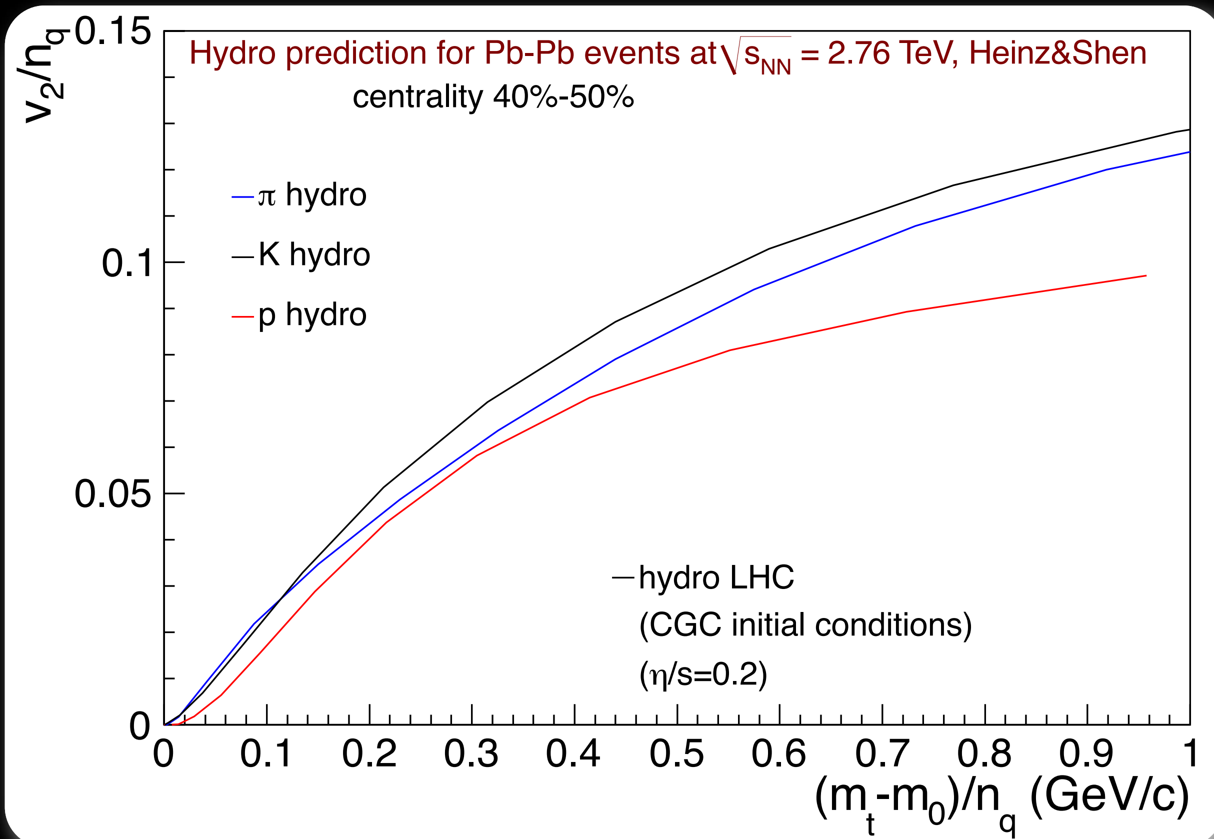
see presentation M. Krzewicki

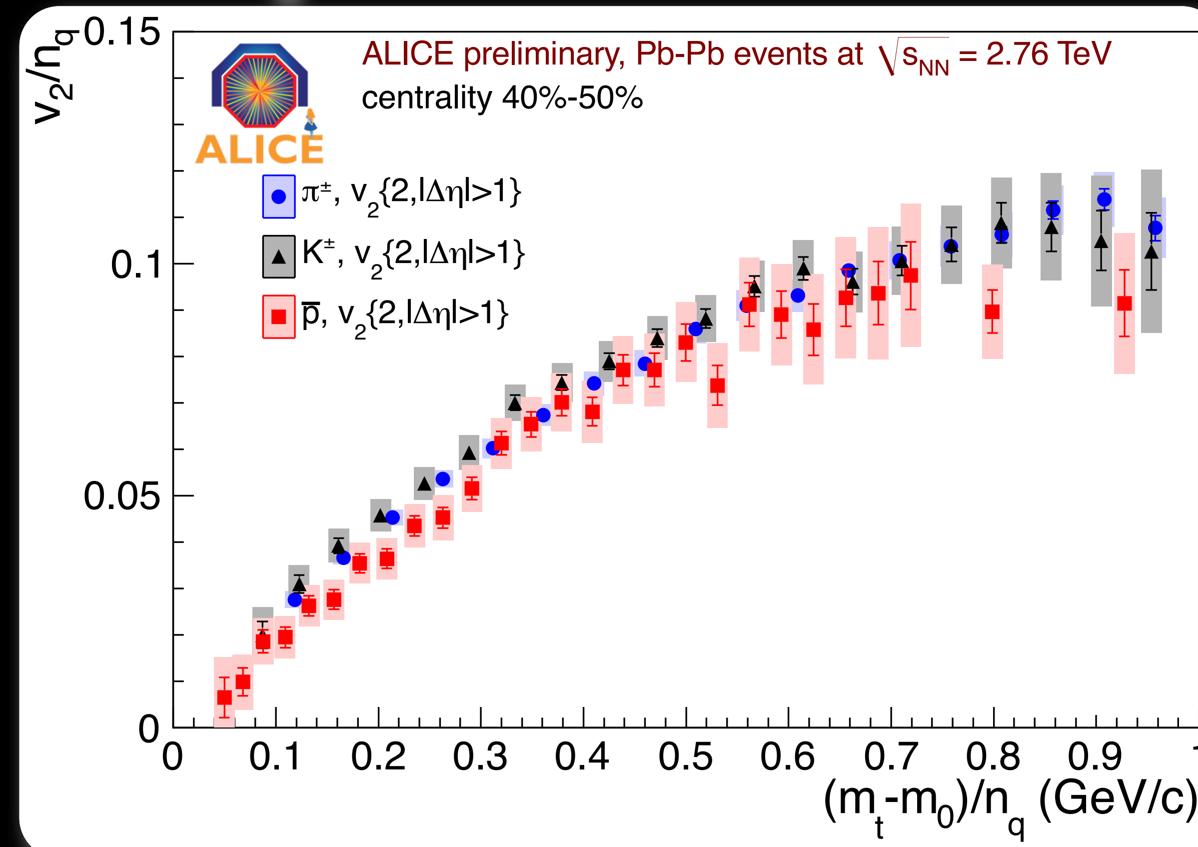
the mass splitting increased compared to RHIC energies

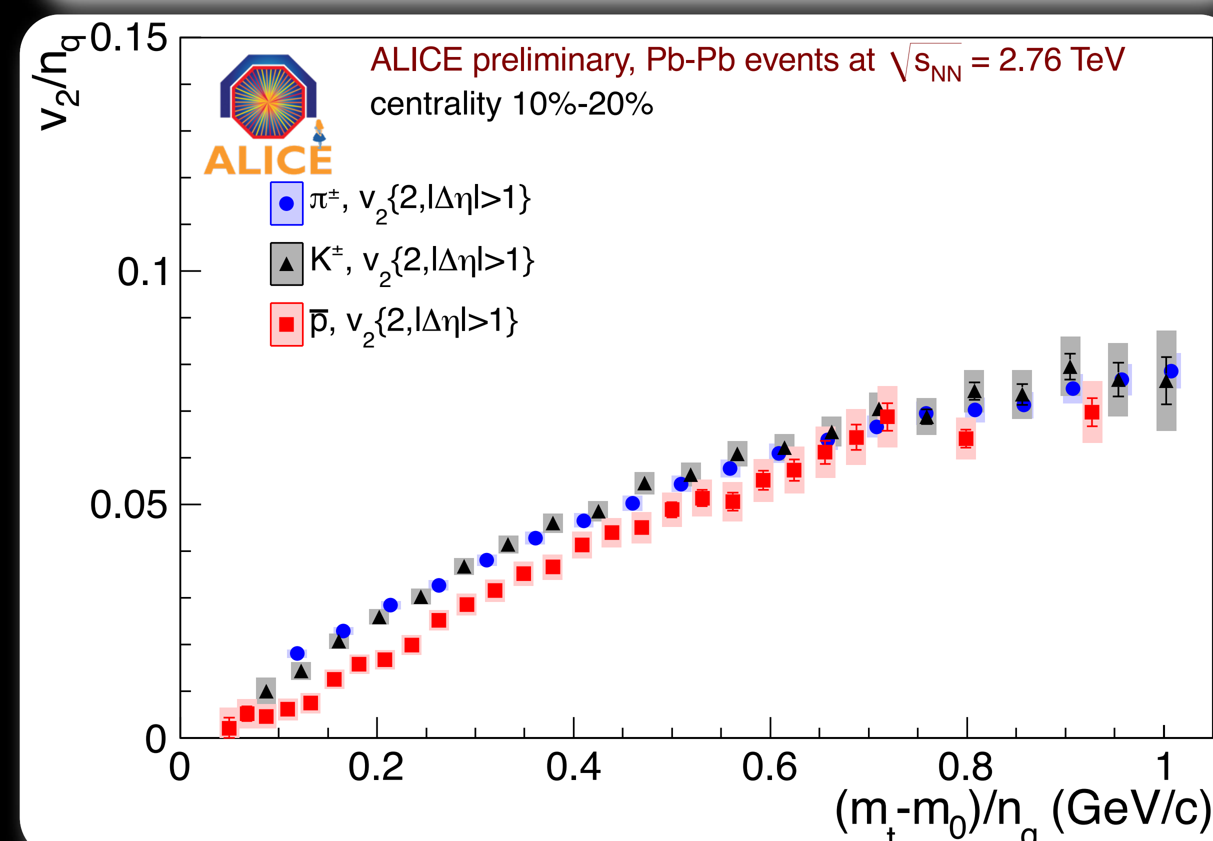
pion and Kaon v_2 are described well with hydrodynamic predictions using MC-KLN CGC initial conditions and $\eta/s = 0.2$

v_2 for identified particles

Hydro: Shen, Heinz, Huovinen & Song, arXiv:1105.3226





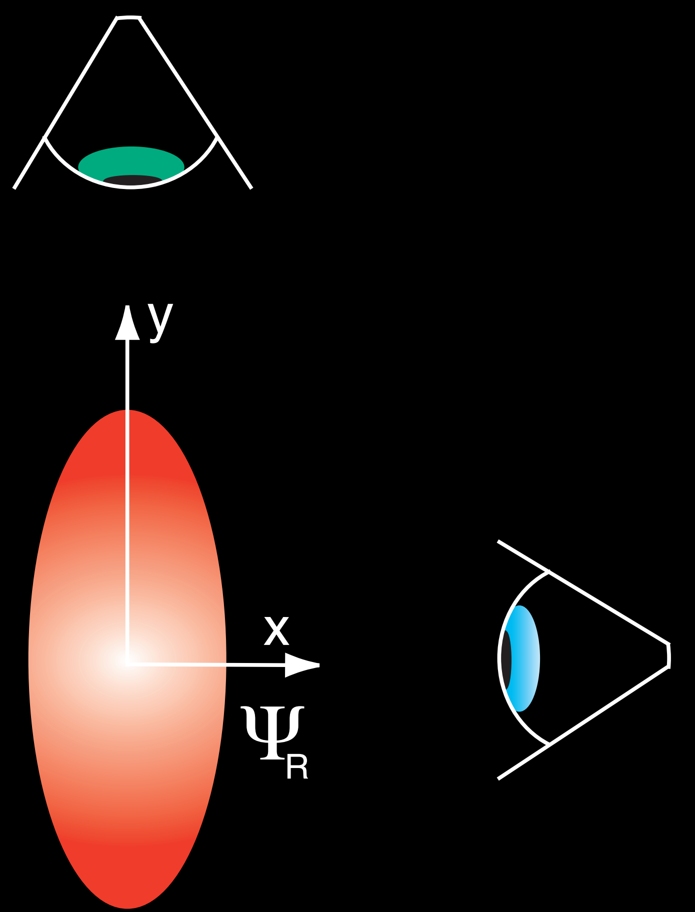


at small $(m_t-m_0)/n_q$ the scaling in the data resemble the scaling as observed in hydrodynamics

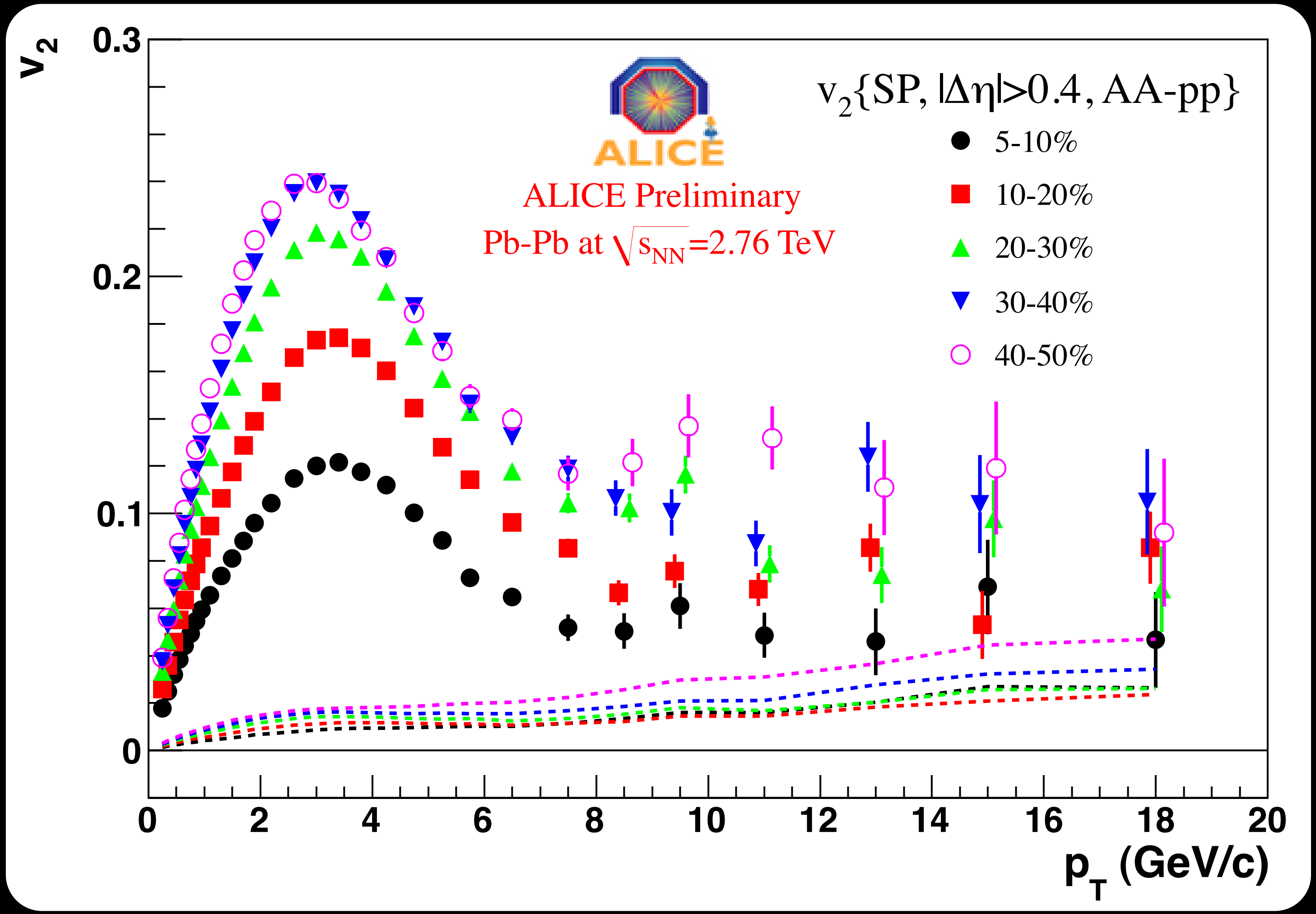
at large $(m_t-m_0)/n_q$ the quark scaling seems to work better

see presentation M. Krzewicki

v_2 at high-p_t



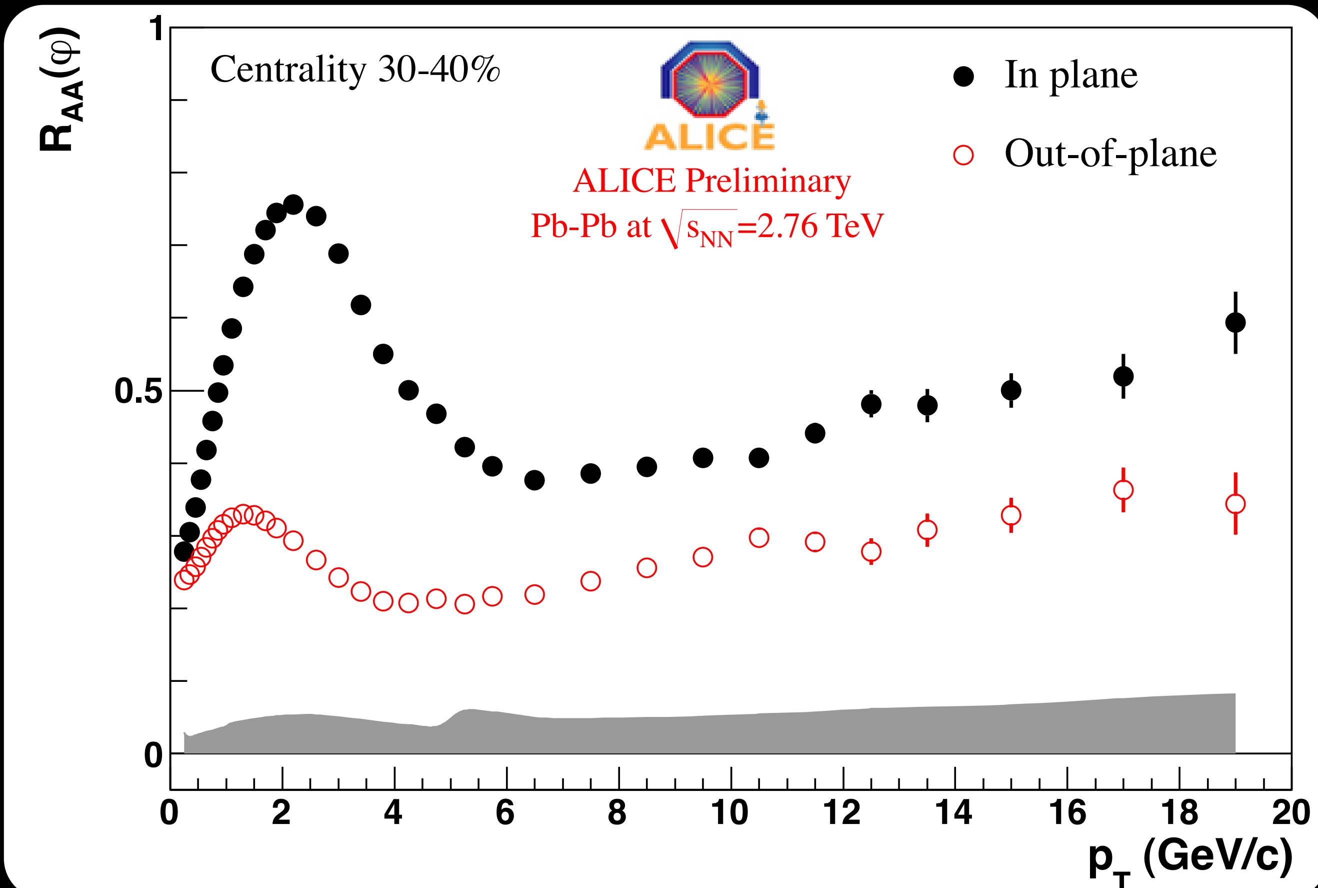
$$v_2 = \langle \cos 2(\phi - \Psi_2) \rangle$$

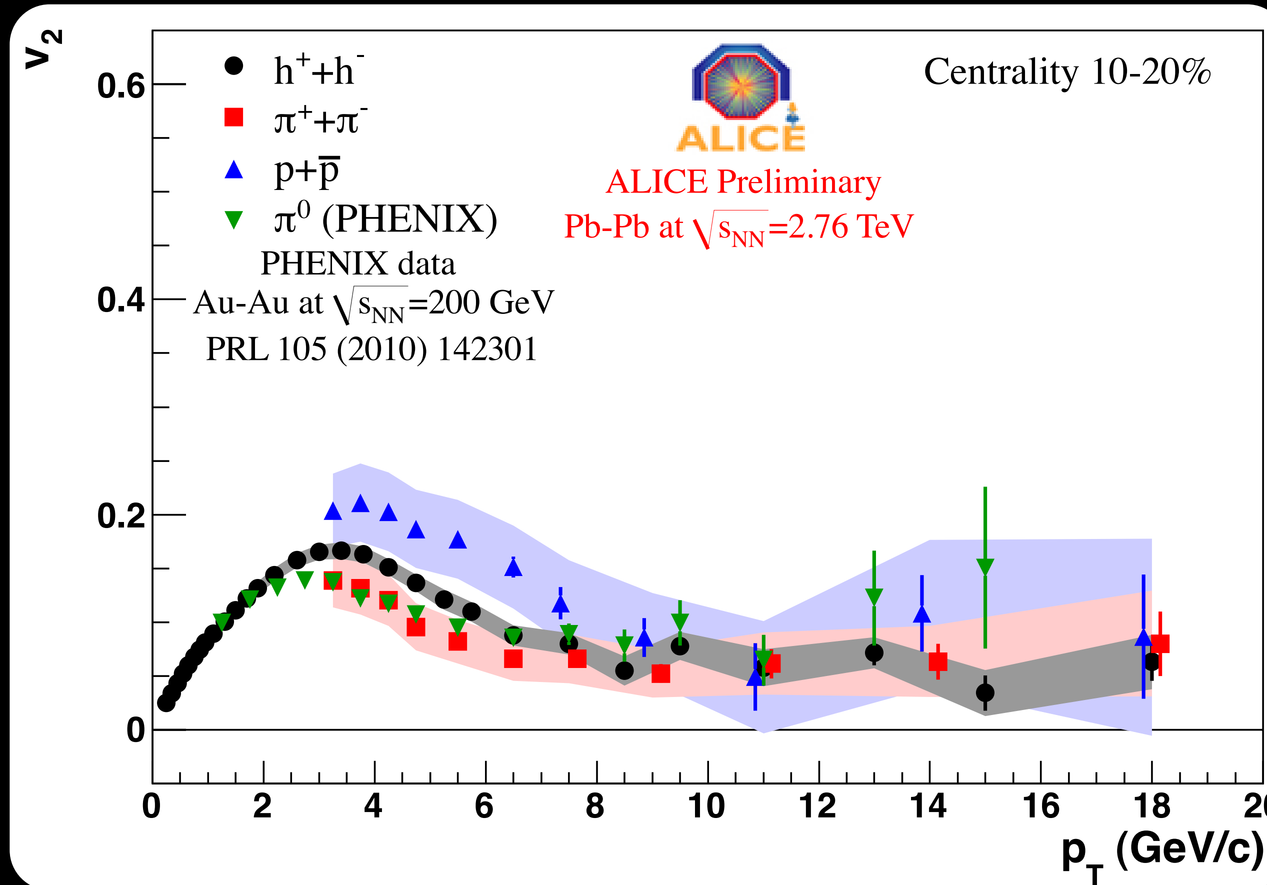


see presentation A. Dobrin

significant v_2 observed at high-p_t which depends on centrality (geometry)

anisotropy at high-p_t





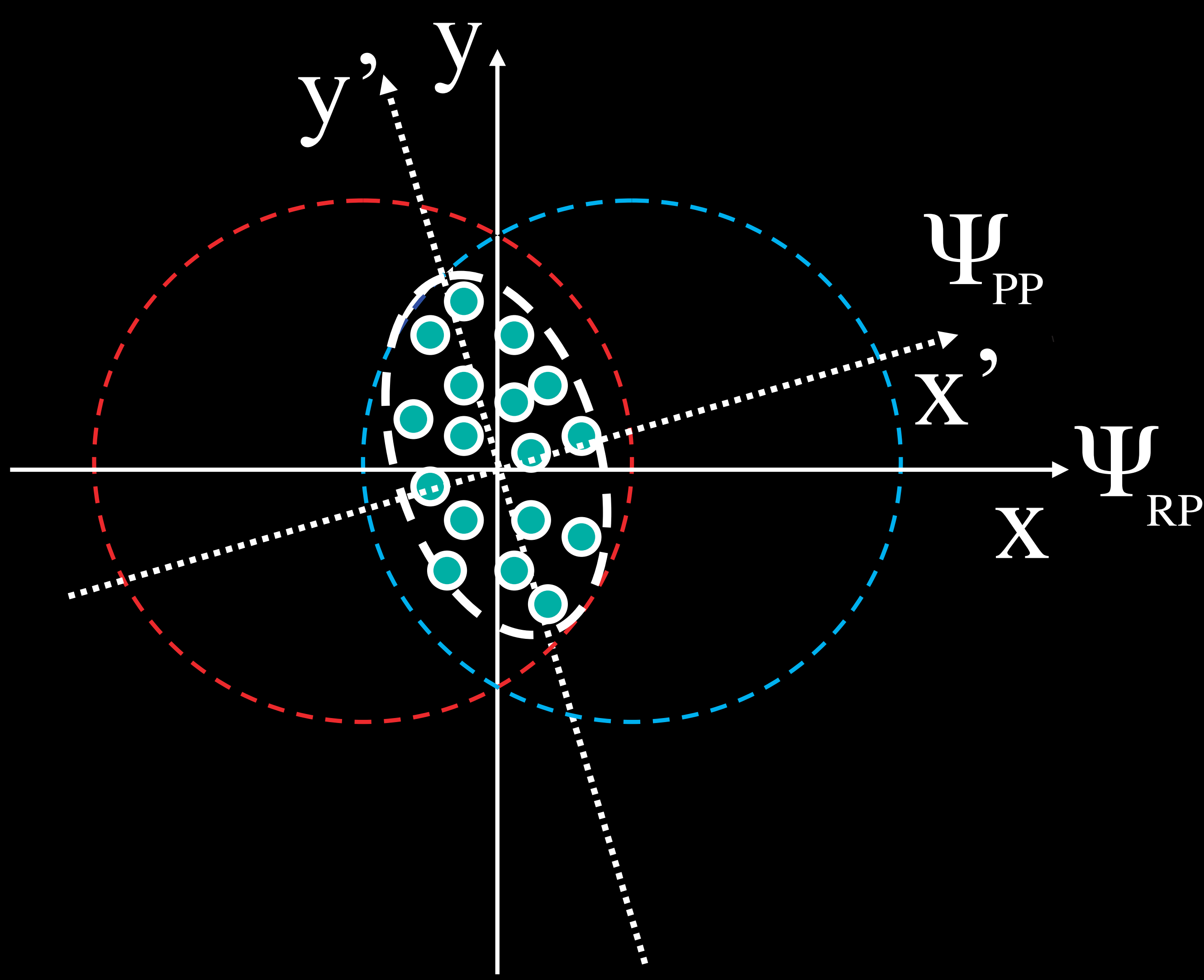
see presentation A. Dobrin

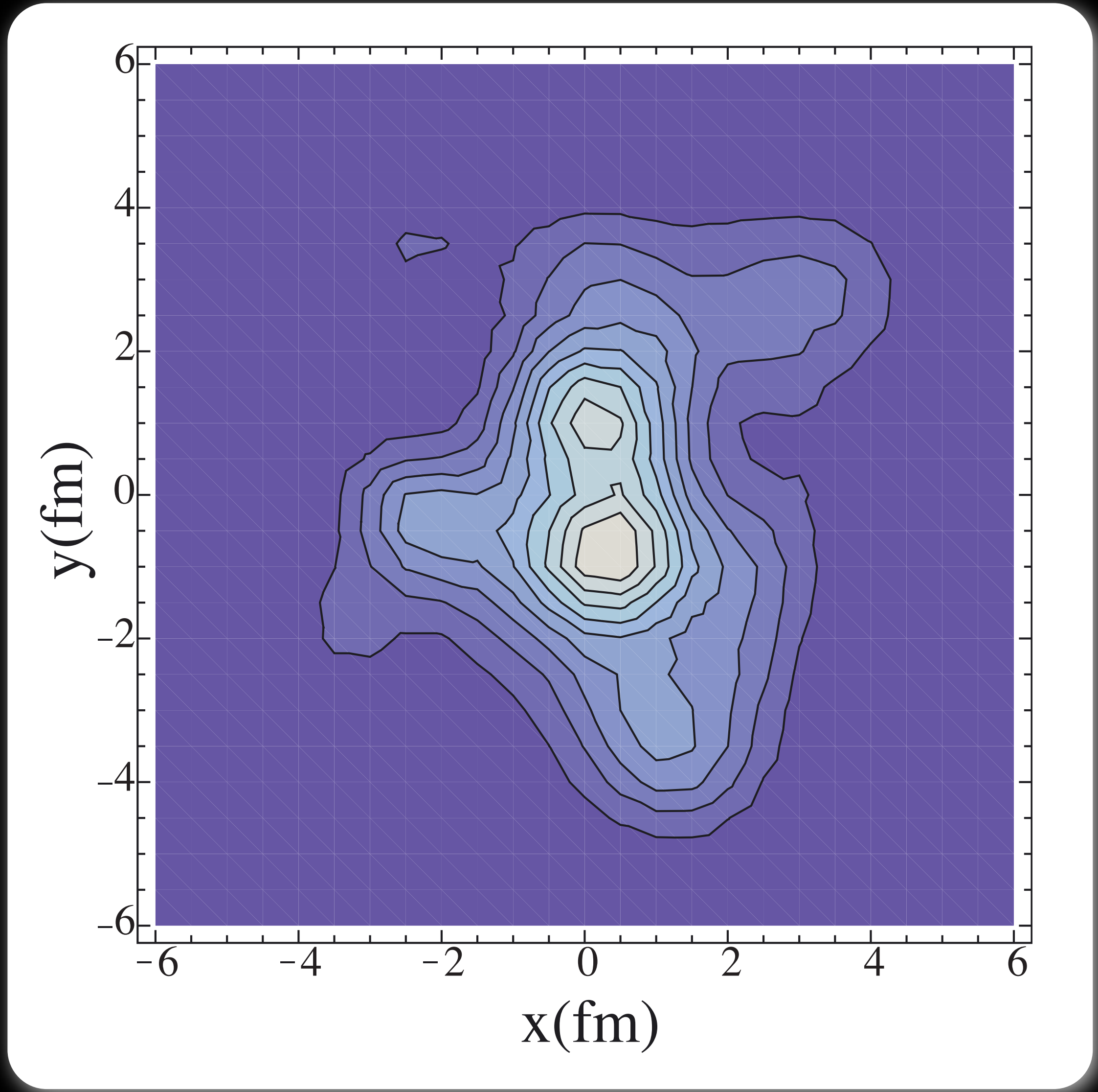
The measured v_2 and R_{AA} gives $R_{AA}(\Phi)$ which strongly depends on the geometry

The proton v_2 is larger than pions at intermediate p_t

Above 8 GeV/c the pion and proton v_2 start to overlap within systematic uncertainties

Anisotropic Flow



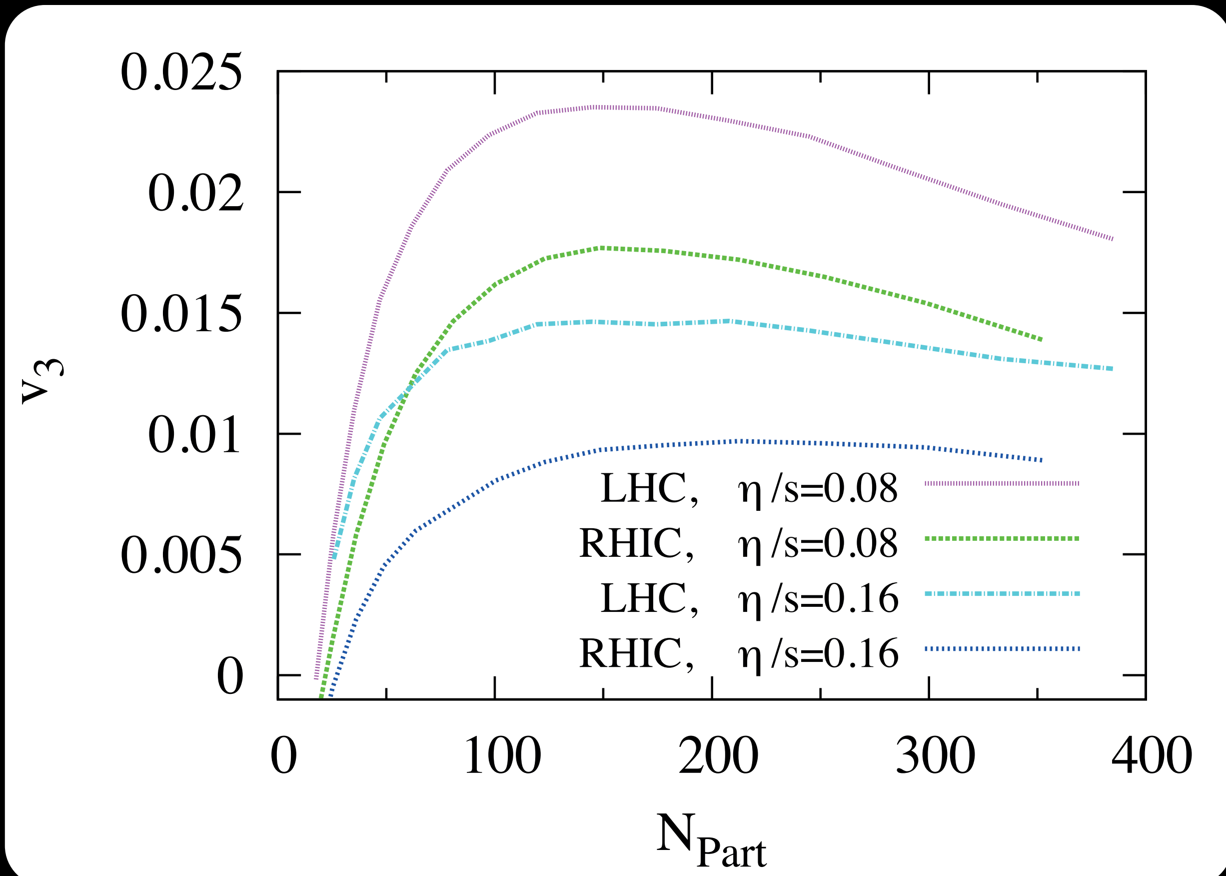


G. Qin, H. Petersen, S. Bass, and B. Muller

initial spatial geometry not a simple almond
may generate higher harmonics!!!

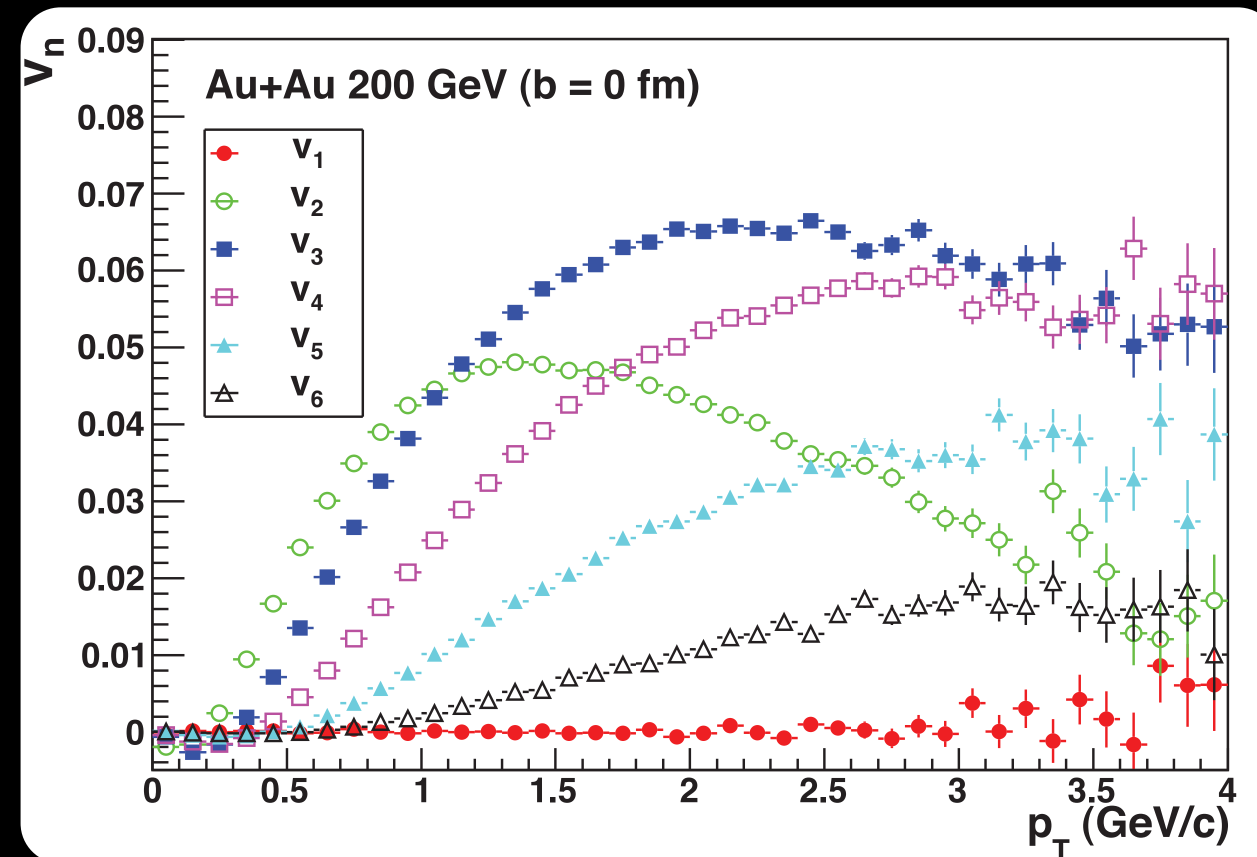
Other Harmonics

Hydro: Alver, Gombeaud, Luzum & Ollitrault, Phys. Rev. C82 (2010)

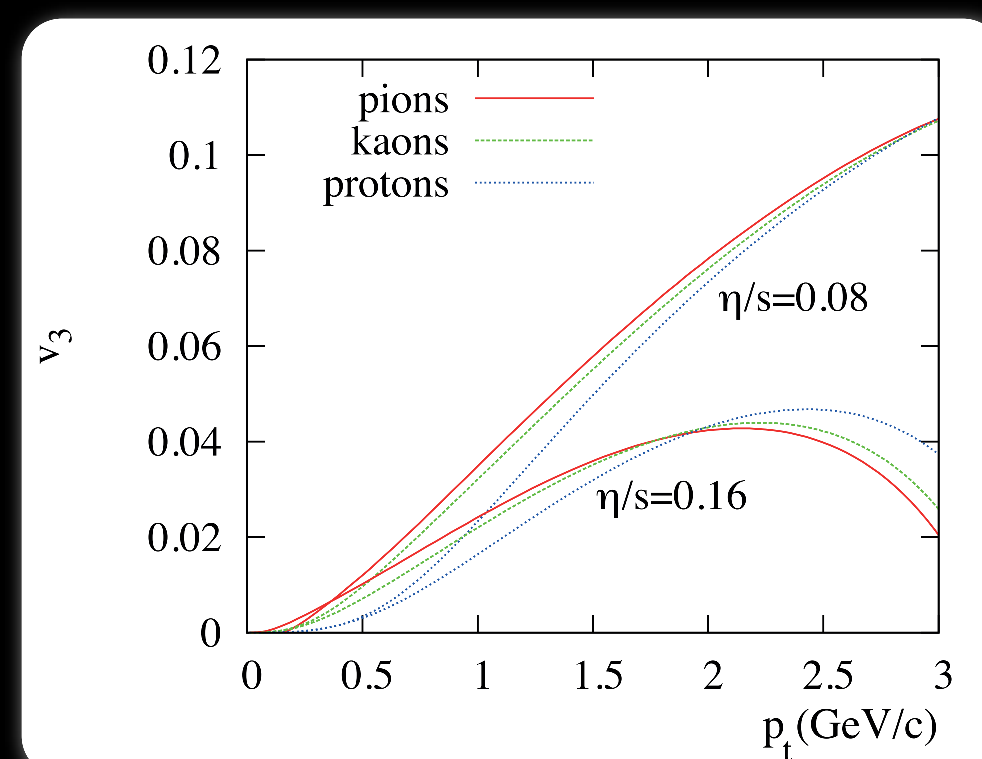


η/s=0.08 MC Glauber
η/s=0.16 MC-KLN CGC

G-L Ma and X-N Wang, arXiv:1011.5249v2



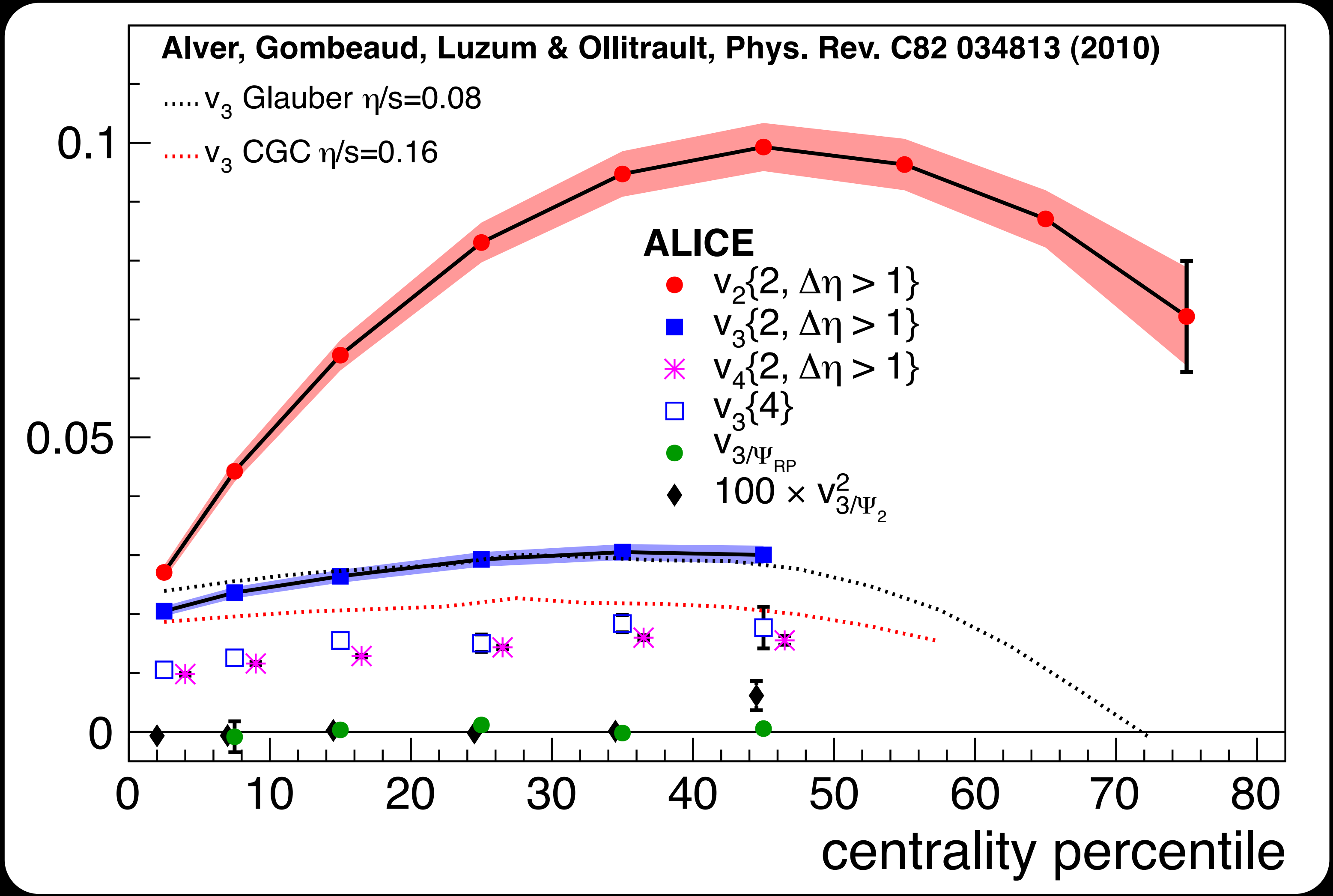
currently "large" uncertainty on initial conditions and η/s by using only v_2; the other harmonics provide important new strong constraints



Triangular Flow

We observe significant v_3 which compared to v_2 has a different centrality dependence

The centrality dependence and magnitude are similar to predictions for MC Glauber with η/s=0.08 but above MC-KLN CGC with η/s=0.16

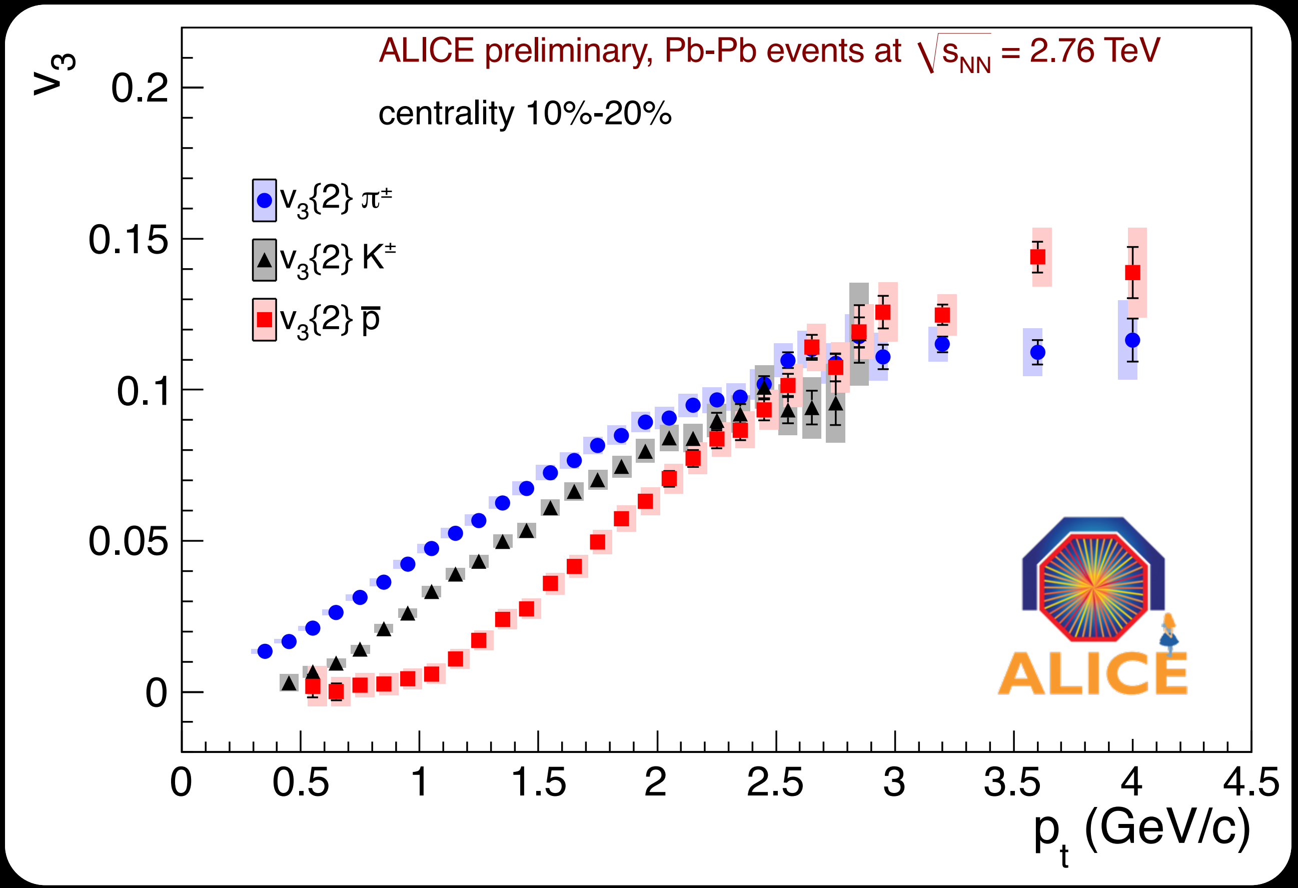


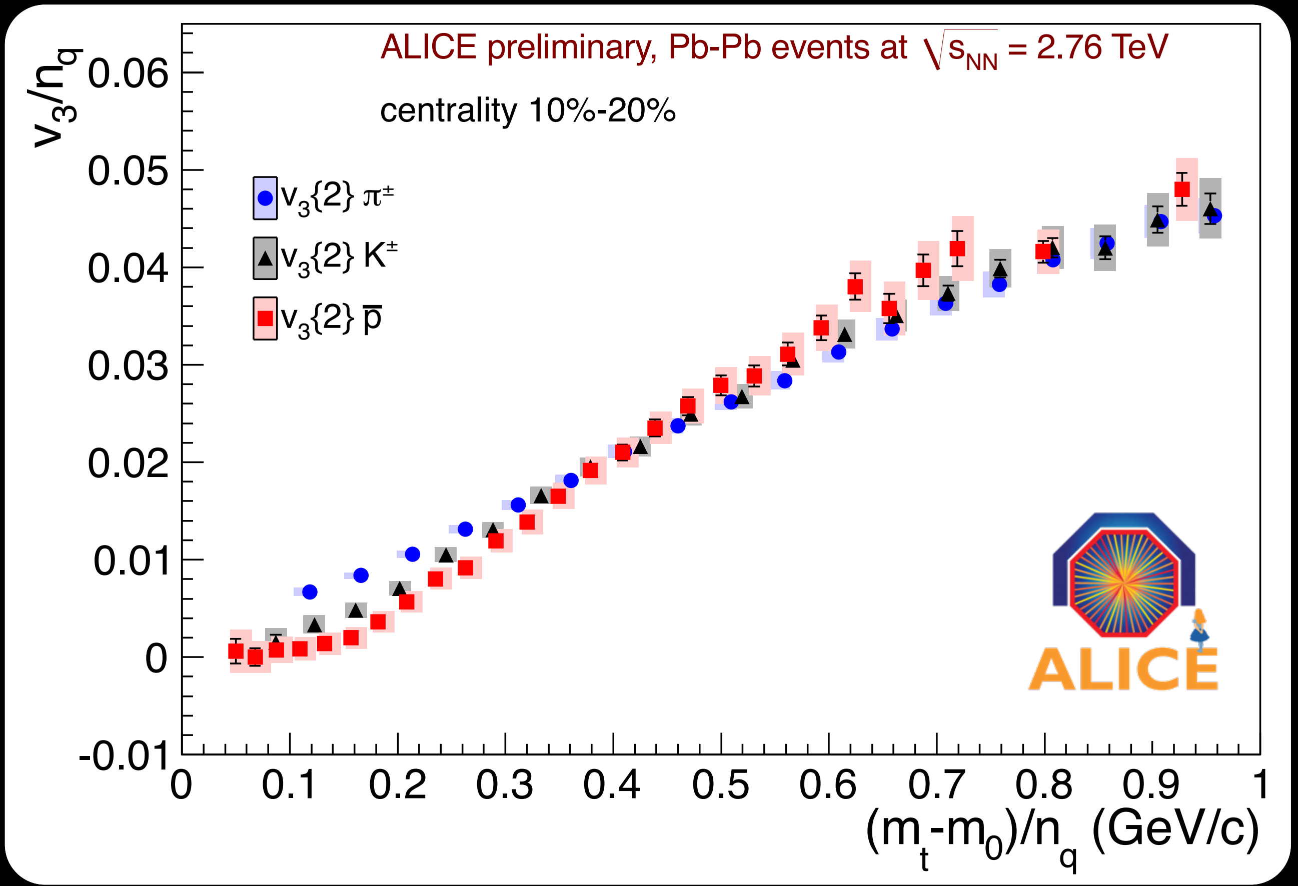
ALICE Collaboration, arXiv:1105.3865

The v_3 with respect to the reaction plane determined in the ZDC and with the v_2 participant plane is consistent with zero as expected if v_3 is due to fluctuations of the initial eccentricity

The $v_3\{2\}$ is about two times larger than $v_3\{4\}$ which is also consistent with expectations based on initial eccentricity fluctuations

Triangular Flow



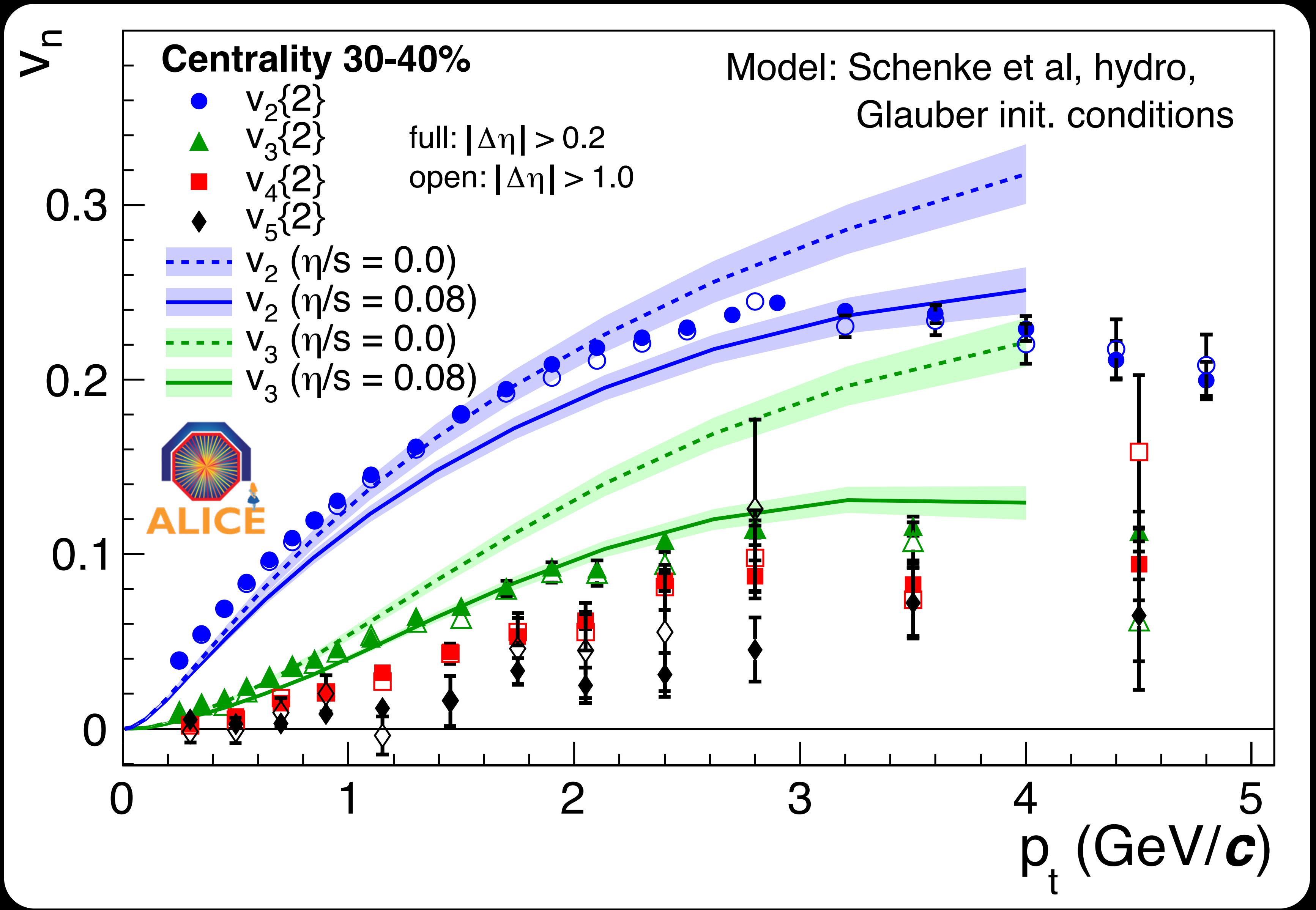


see presentation M. Krzewicki

The behavior of v_3 as function of p_t for pions, Kaons and protons shows the same features as we already observed for v_2

(we observe the mass splitting and, in addition, the crossing of the pions with protons at intermediate p_t, which for v_2 was considered as a signature for coalescence/recombination)

Other Harmonics



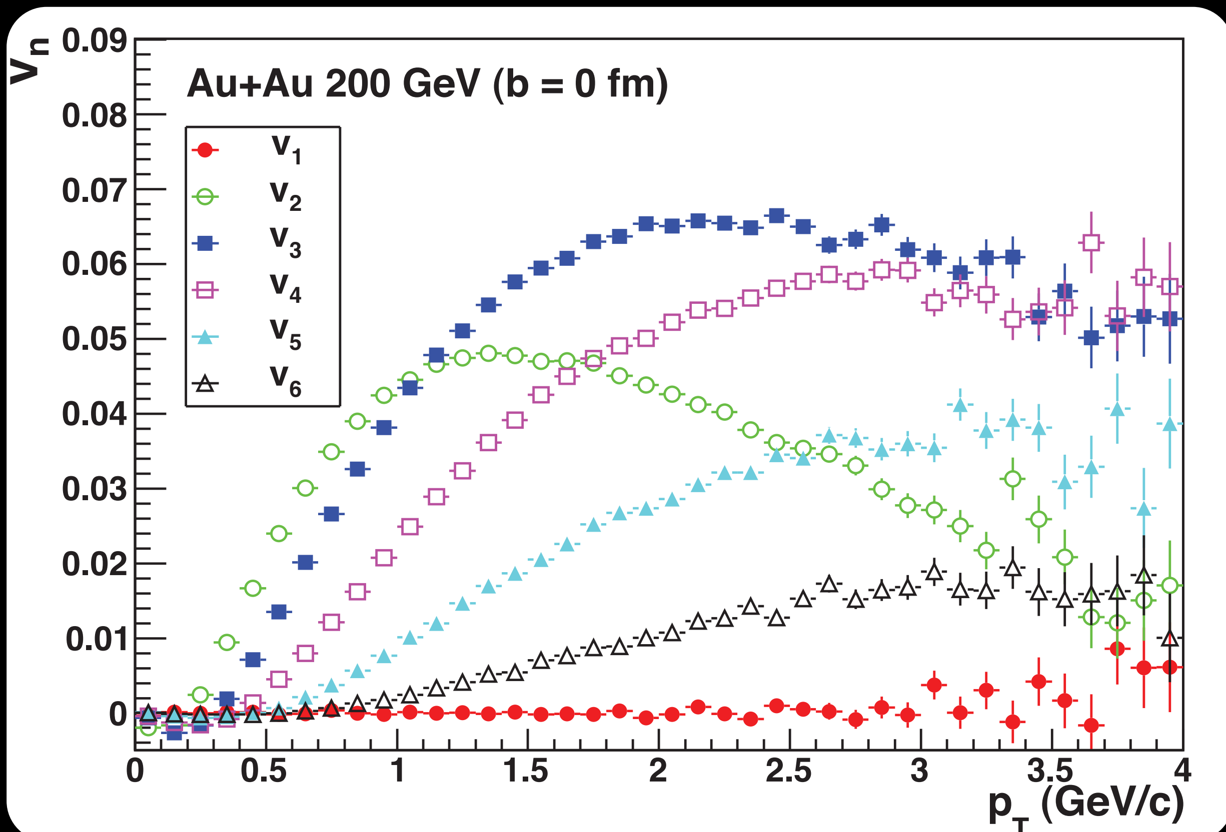
ALICE Collaboration, arXiv:1105.3865

see presentation A. Bilandzic

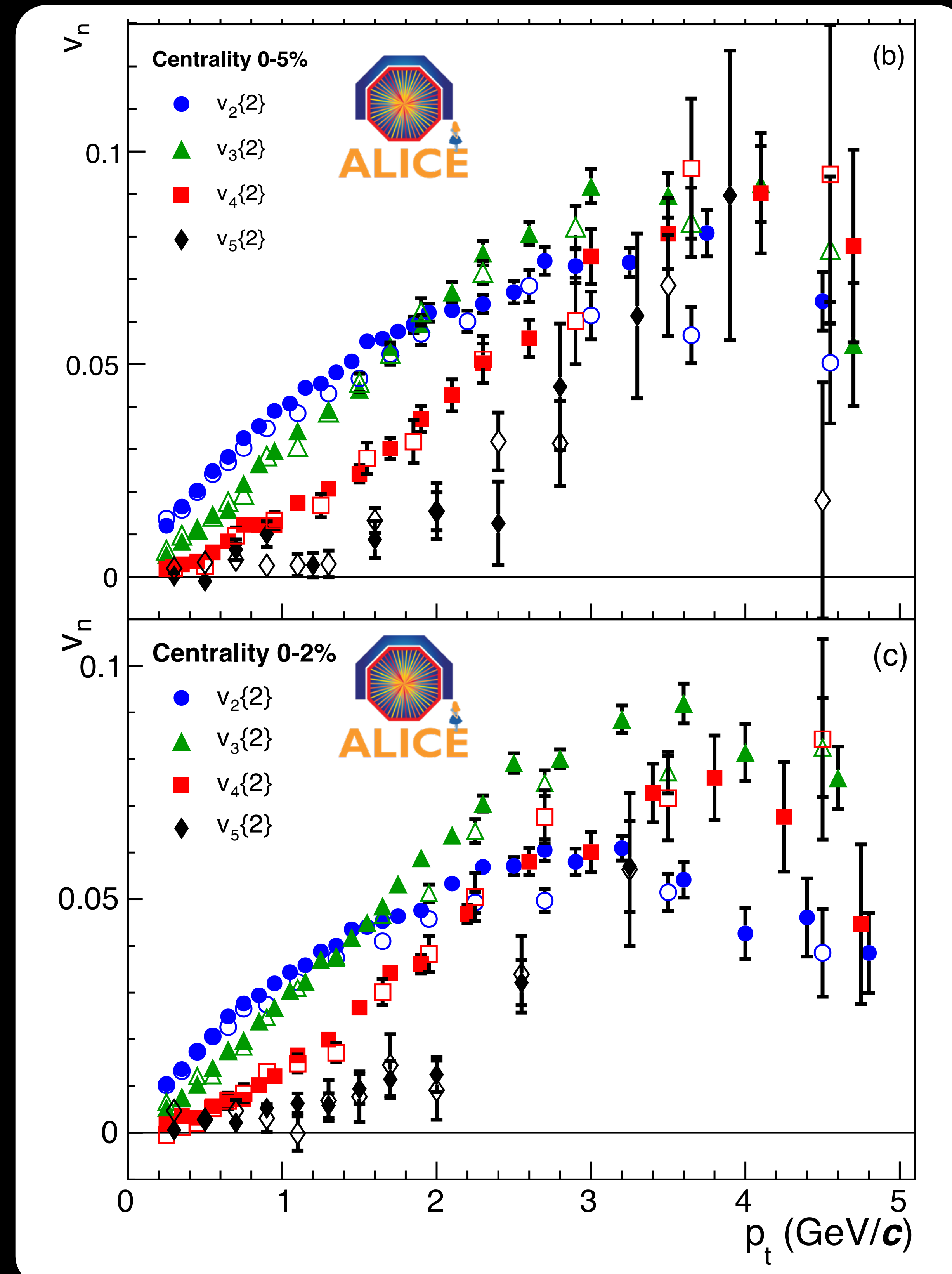
The overall dependence of v_2 and v_3 is described

However there is no simultaneous description with a single η/s of v_2 and v_3 for Glauber initial conditions

Other Harmonics



G-L Ma and X-N Wang, arXiv:1011.5249v2

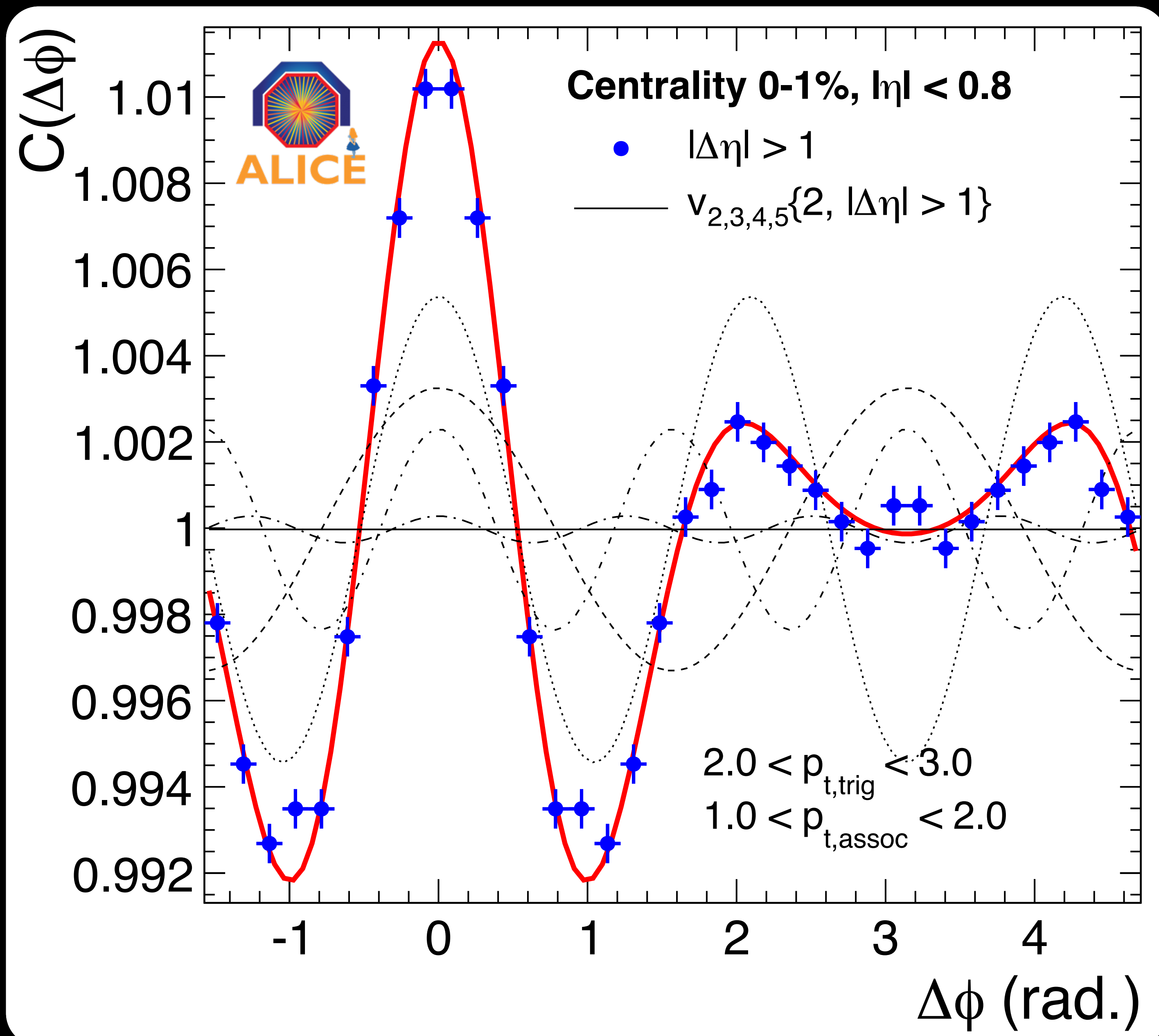


ALICE Collaboration, arXiv:1105.3865

- For central collisions at intermediate p_t the higher harmonics v_3 and v_4 cross v_2 and become the dominant harmonics
- For more central collisions this occurs already at lower p_t

Other Harmonics

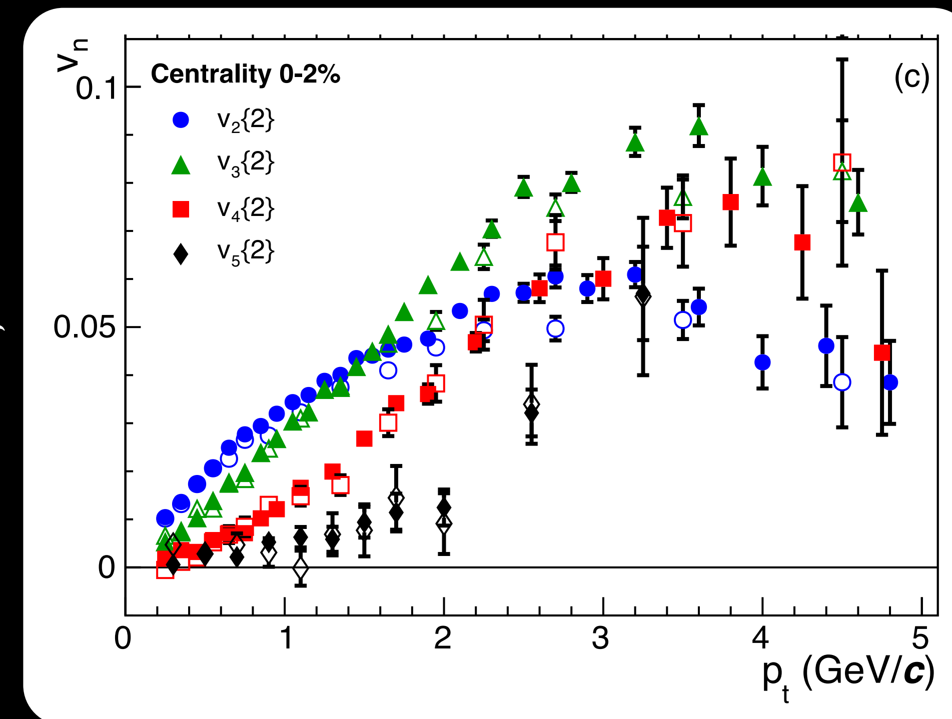
ALICE Collaboration, arXiv:1105.3865



see presentations J-F. Grosse-Oetringhaus and A. Adare

$$C(\Delta\phi) \equiv \frac{N_{\mathrm{mixed}}}{N_{\mathrm{same}}} \frac{\mathrm{d}N_{\mathrm{same}}/\mathrm{d}\Delta\phi}{\mathrm{d}N_{\mathrm{mixed}}/\mathrm{d}\Delta\phi}$$

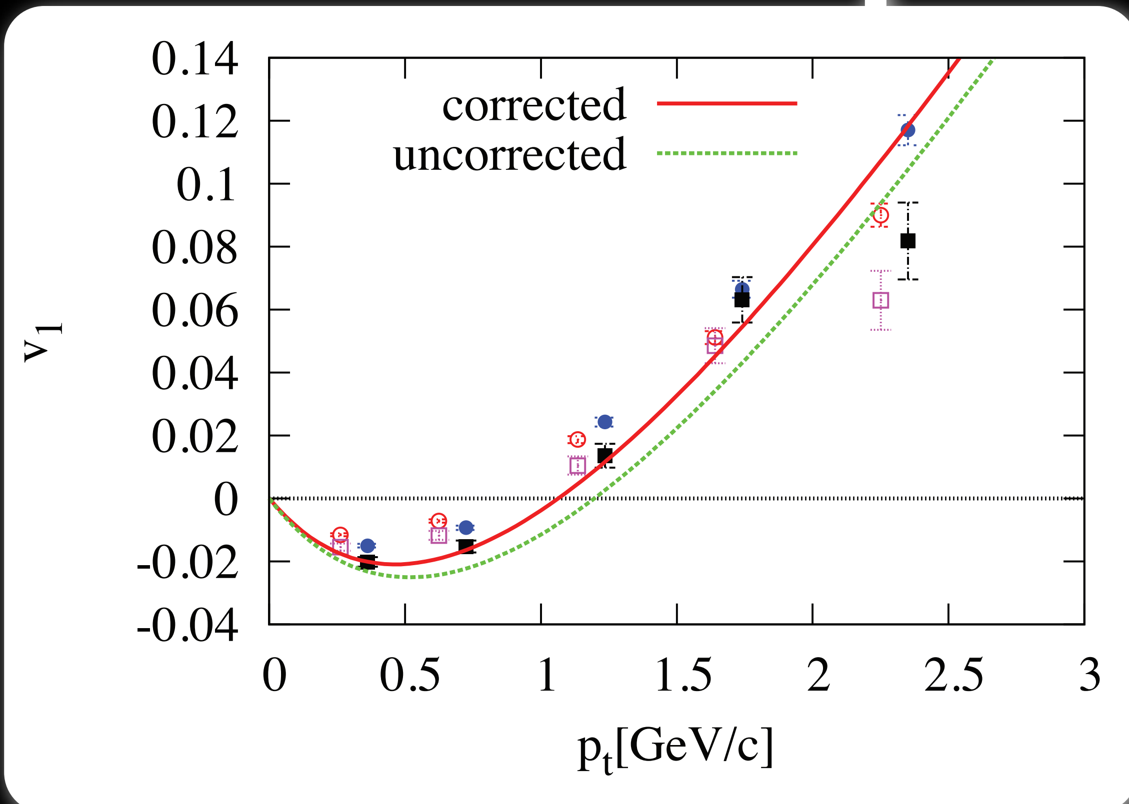
ALICE Collaboration, arXiv:1105.3865

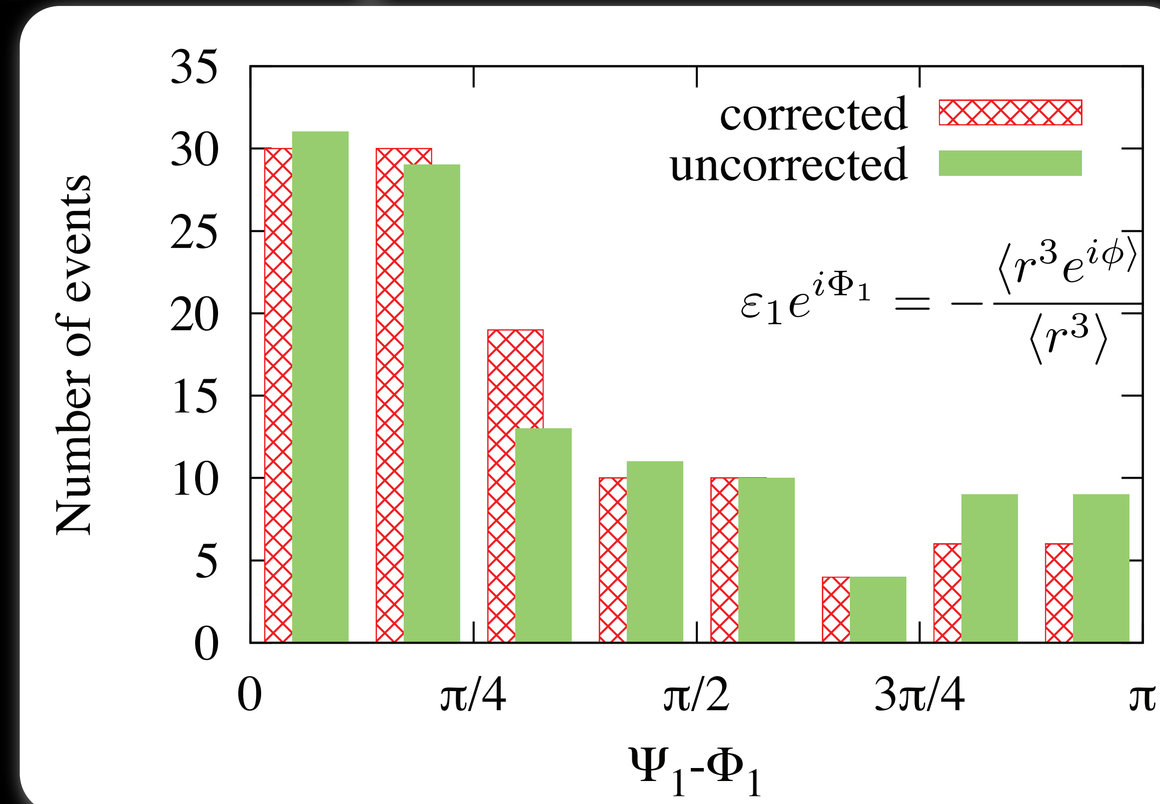


We observe a doubly-peaked structure in the azimuthal correlation function opposite to the trigger particle before the subtraction of v_2

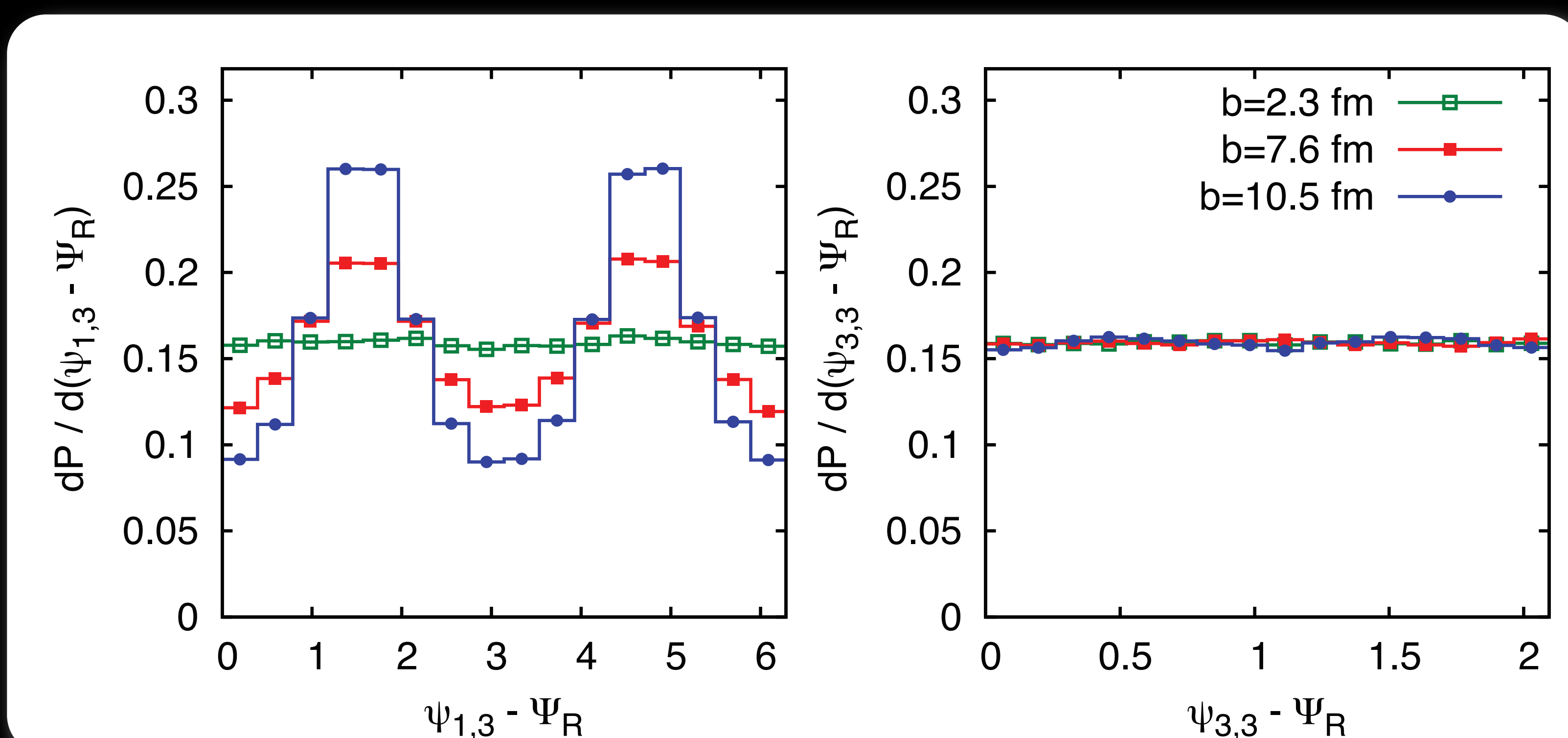
The red line shows the sum of the measured anisotropic flow Fourier coefficients. Those flow coefficients give a natural description of the observed correlation structure

η-even v₁





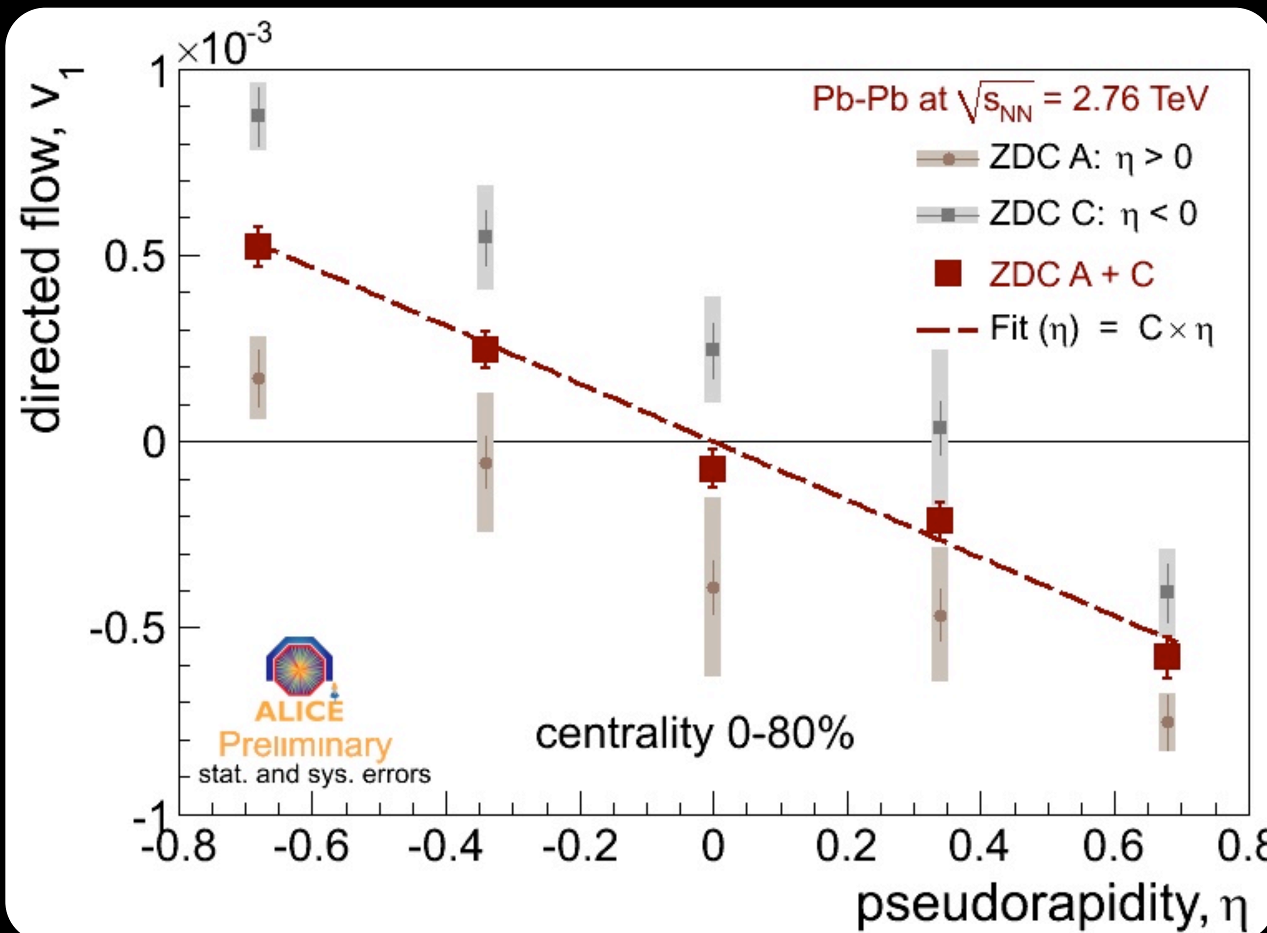
F. Gardim, F. Grassi, Y. Hama, M. Luzum, J-Y Ollitrault, arXiv:1103.4605

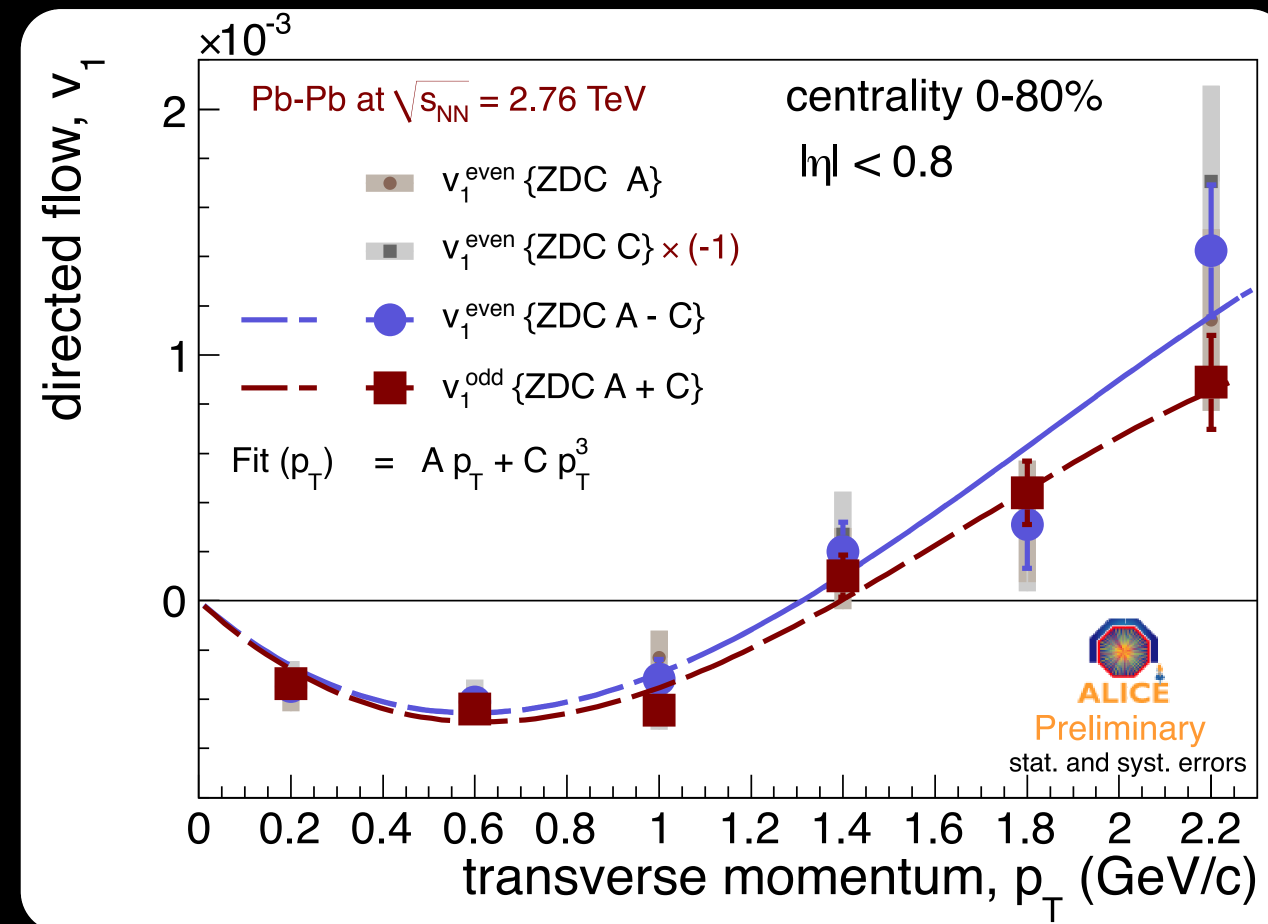


Theory predicts a η-even v₁ which has an non trivial p_t dependence

D. Teaney, L Yan arXiv:1010.1876

v_1





see presentation I. Selyuzhenkov

We measure with the "spectators" in the ZDC's the η-odd directed flow which looks as measured at RHIC

When we measure η-even directed flow we find a non vanishing signal in both the ZDCs which has a similar p_t dependence as the η-odd directed flow

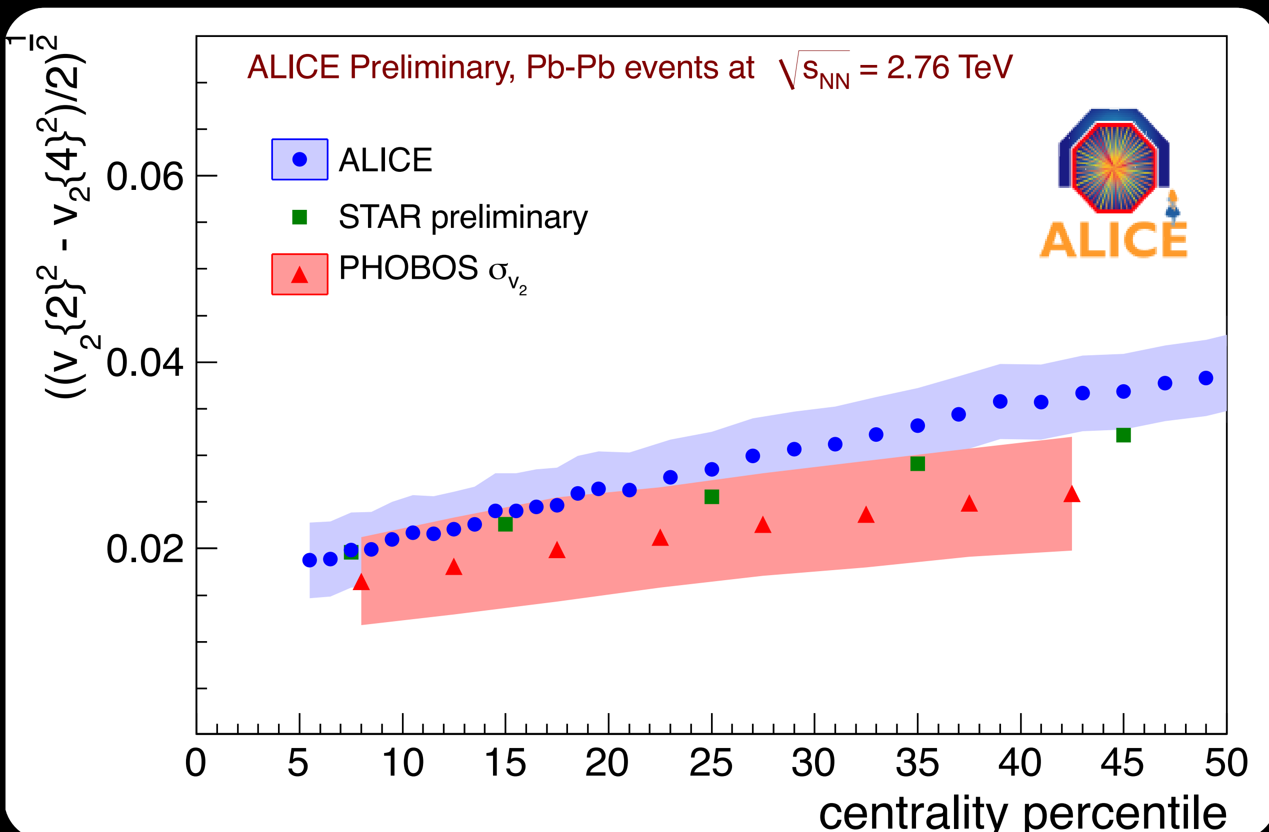
Conclusions

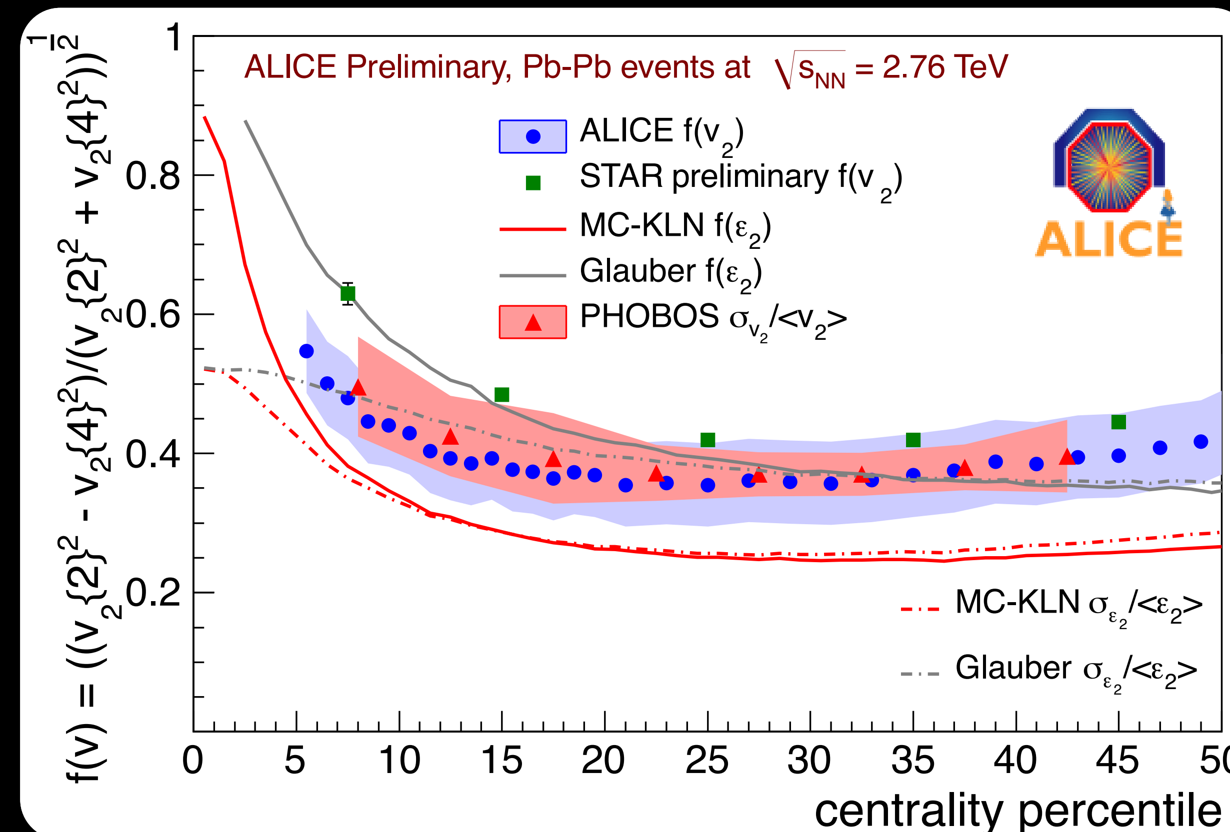
- We observe stronger flow than at RHIC which is expected for almost perfect fluid behavior
- We have made the first measurements of v_3, v_4 and v_5, and have shown that these flow coefficients behave as expected from fluctuations of the initial spatial eccentricity
  - provides new strong experimental constraints on η/s and initial conditions
- The measured flow coefficients at lower p_t are in agreement with expectations from viscous hydrodynamic calculations
  - Currently the measurements are not simultaneously described by hydrodynamical model calculations using one initial spatial eccentricity and η/s

Thanks

Backup

v_2 Fluctuations



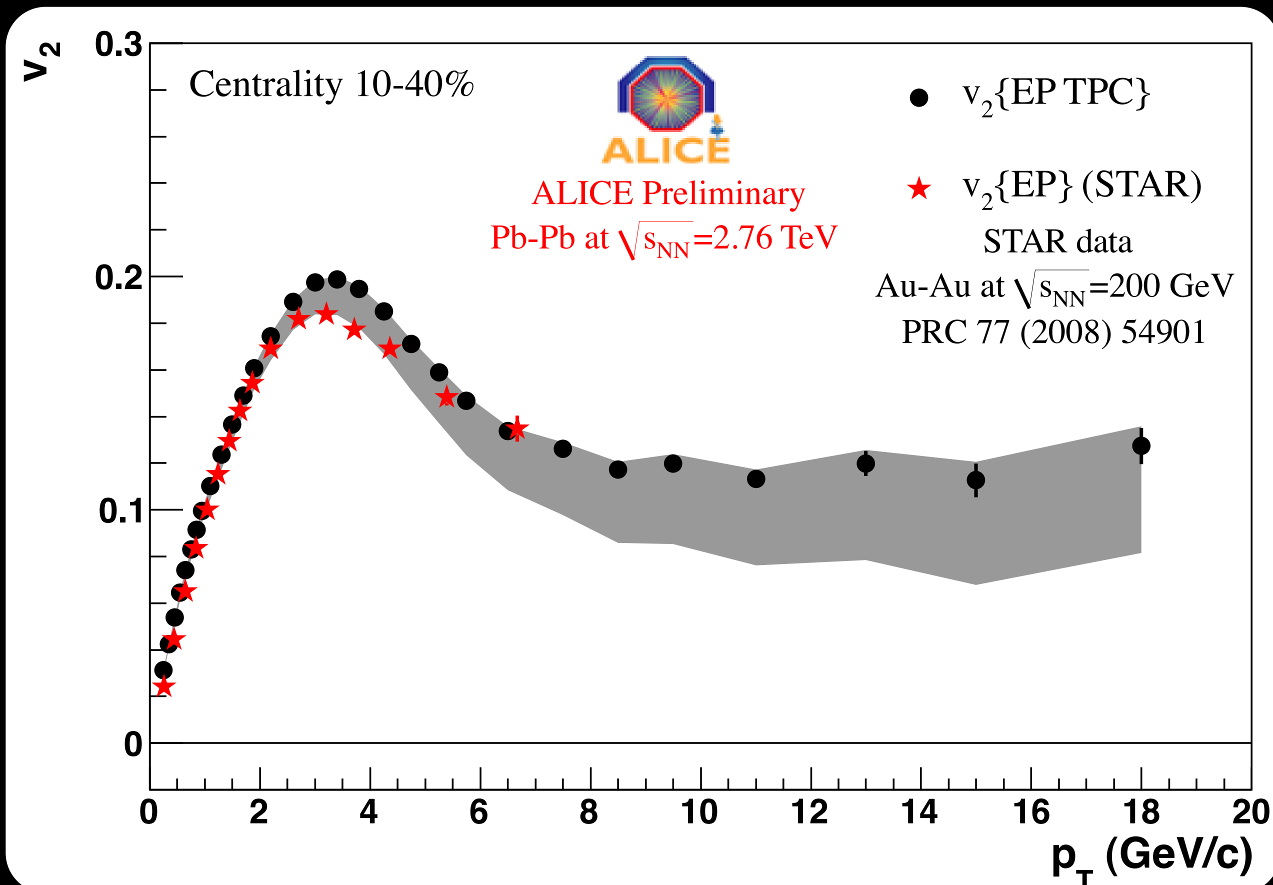


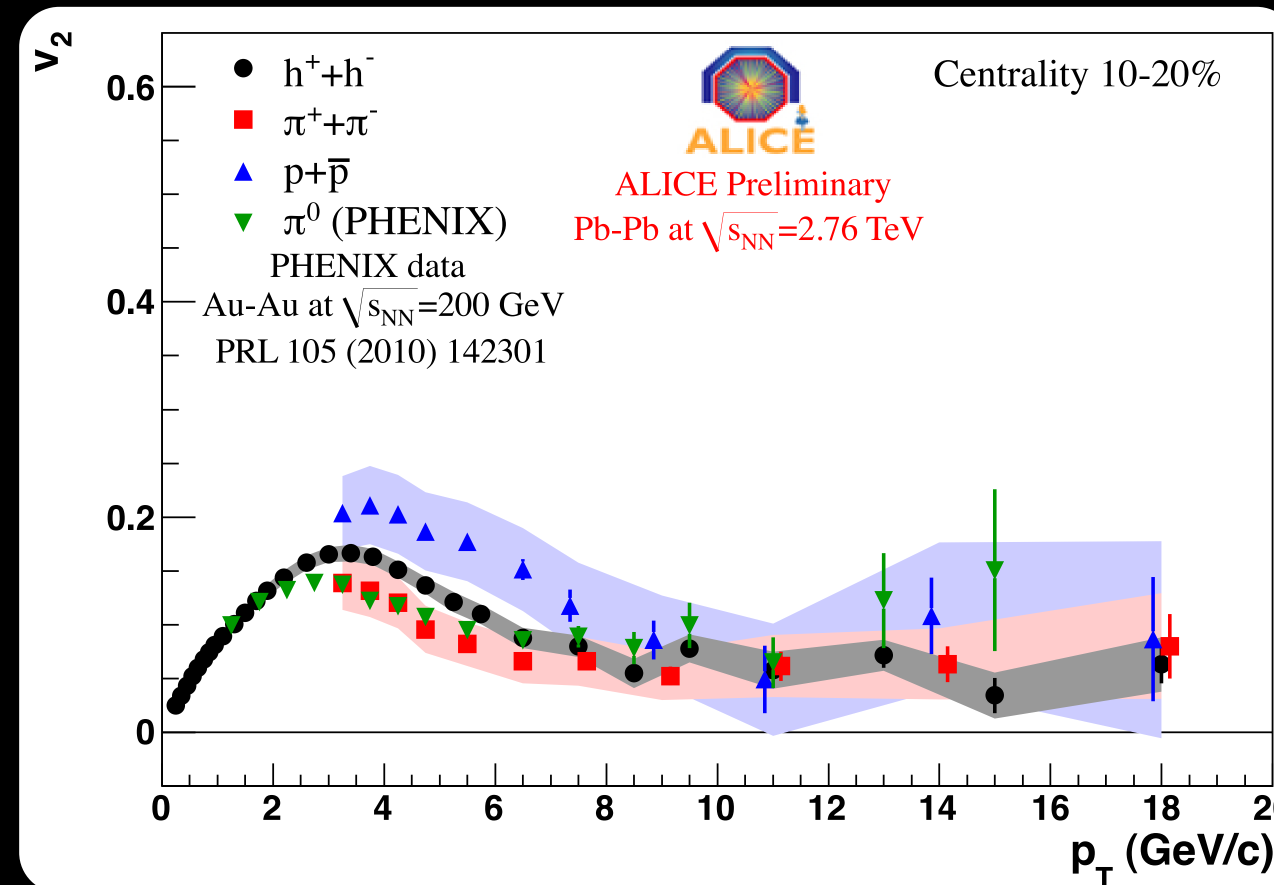
$$\sigma_{v_n} \simeq \frac{1}{2}\left(v_n^2\{2\} - v_n^2\{4\}\right)^{\frac{1}{2}}$$

$$\frac{\sigma_{v_n}}{v_n} \simeq \left(\frac{v_n^2\{2\} - v_n^2\{4\}}{v_n^2\{2\} + v_n^2\{4\}}\right)^{\frac{1}{2}}$$

For more central collisions the data is between MC Glauber and MC-KLN CGC

pion and proton v_2





see presentation A. Dobrin

At higher p_t charged particle v_2 similar to RHIC

The proton v_2 is larger than pions at intermediate p_t

Above 8 GeV/c the pion and proton v_2 start to overlap within systematic uncertainties